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THE MECHANISM OF SEPARATION IN THE LOUVER TYPE DUST SEPARATOR

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SUMMARY

The investigation was conducted to gain a knowledge of how the louver separates the dust particles and why some of the particles are able to escape separation. A preliminary study of the particle paths in a two dimensional louver separator was conducted to determine which design features are conducive to good performance. To test the conclusions of the preliminary study, a thirty degree sector of a conical separator was constructed and its performance studied.

The effectiveness of the separator was evaluated by determining the effect of per cent blowdown, initial air velocity, and initial dust concentration on the per cent of the initial dust separated. The particle size distributions of the input dust, the separated dust, and the non-separated dust were compared to bring out the effectiveness of the separator on different particle sizes. The particle paths in the separator were studied and correlated to the separator performance. Throughout the investigation the particle paths were made visible by proper illumination.

It was found that the over all air flow pattern through the separator was the controlling factor in the performance. Hence the shape of the housing on both sides of the louver is of utmost importance. The flow pattern with the same flow through each louver opening was found to be the most desirable. This flow pattern was present when the velocity of the blowdown partion of the inlet air stream was constant from inlet to blowdown. The effect of the per cent blowdown was correlated to changes in

the air flow pattern, and it was found that the performance of the separator could be maintained at low blowdown flows if the louver housing was designed to provide a desirable flow pattern at the specified blow-down flow.

From the particle path studies it was concluded that the most effective louver blade shape separates the region of particle impacts with the blade from the region where the air is passing between the blades. The particle size studies showed that the separator was effective on particles as small as ten microns and that the separator was more effective on particles above forty microns. The data from the separator showed that the per cent of the initial dust separated was essentially independent of the initial air velocity and of the initial dust concentration. An approximate analysis of the particle paths was developed which is helpful in explaining the trends in the experimental data.

CHAPTER I

INTRODUCTION

The problem.--The louver dust separator, Figure 1, is an inertial type separator. It is characterized by a stream of dust laden air incident upon a row of blades or vanes which form the louver face. The larger portion of the air stream, clean air, turns and passes through the blades and the smaller portion of the air stream, blowdown, continues in its original direction without passing through the louver face. The blades are so arranged that the dust because of its high inertia is unable to pass through the blades and is concentrated in the blowdown air stream.

The louver separator has been manufactured and used for some time; but, previously very little has been known of the mechanism by which it separates the dust particles from the air. The previous extent of understanding is best expressed by the statement that it is easier for air to negotiate a sharp turn than it is for high inertia dust particles.

Previous work.--Harwell (1) in 1950 and Matheson (2) in 1952 submitted at the Georgia Institute of Technology theses on the louver dust separator. Both of these studies were for the most part analyses of performance data from the separator. Neither of the two analyses provided an understanding of the separation process. A literature search that was made by Matheson showed that there is very little in the literature that is helpful in understanding the mechanism of separation.

Objective.--This investigation has had as its first object an understanding of the process of separation. This involves a knowledge of why the particles that are separated are not able to pass through the louver blades and of how some particles manage to escape separation. The second object of the investigation was to use this knowledge of the separation mechanism to design a separator with improved performance. The redesigned separator was to embody features which would maximize the forces and effects causing particle separation and minimize those causing particles to pass between the blades.

CHAPTER II

PRELIMINARY STUDIES

Method of investigation.--The investigation was conducted in two parts. For the preliminary studies the apparatus of Matheson was modified and used to study the mechanism of separation. The second part of the investigation consisted of the design, construction, testing and analyzing of a new separator.

Almost all that was learned in this investigation was the result of being able to follow the paths of the particles as they passed through the separator. The particle paths were made visible by a system, Figure 1, developed during the study. This system was suggested by the tindall meter (3) and uses the same principle. A very intense beam of light is focused on the particles, the beam of light being perpendicular to the direction of the particle motion. The paths of the particles in the plane formed by the light beam and the particle motion are then visible provided the background is completely dark.

Matheson's apparatus was modified, Figure 1, so that this system could be used to follow the particle paths. A one half inch by eight inch glass window was fitted into the front wall of Matheson's separator to admit the light beam. The bottom, all interior walls and the louver blades were painted flat black to serve as a dark background for the illuminated particles and to keep down reflected light. It was necessary to replace Matheson's lucite cover plate with a glass cover because a maze of fine scratches on the surface of the lucite became illuminated by reflected light and were indistinguishable from particle paths. A standard photographic reflector spot bulb was used as a light source. A lens of about eight inch focal length was used to focus the light on the particles. With this arrangement the particles could be seen as thin threads of light as they passed through the high intensity beam. Although this arrangement illuminated only about a one half inch band through the separator, the entire pattern of particle paths could be determined by moving the beam to all parts of the separator.

Evaluation of the performance of Matheson's separator.--Immediately upon observing the paths of the particles in the separator it was evident that in the past the importance of the effects of particle inertia and of particle impacts with the louver blades had been underestimated. In fact a number of the larger particles would strike the louver face and rebound with a high enough momentum to cause them to cross the air stream and strike the front wall of the separator.

By studying the particle paths it was seen that the separating effect of the blade shape used by Matheson was almost entirely dependent upon the momentum of the particle after an impact. To understand how the blade separates examine the path of a representative particle (particle A Figure 2). Particle A enters the separator in a straight line path in the direction of the incoming air stream. No particles could be observed that did not enter the separator along such a straight line path. Let particle A be a particle that just misses the tip of a blade so that particle A will penetrate well into the opening between the blades before impact and hence will be a difficult particle to separate. As particle A approaches the louver face there is no observable deviation from its straight line path until it passes close to the tip of a blade. After the particle just misses the tip of the blade it begins to be deflected by the drag of the air passing between the blades. Figure 3 shows a sketch of the stream lines near the louver blades. The drag deflects the particle only about five degrees before the particle collides with the blade surface. Particle A makes a "good" impact with the blade surface. A "good" impact is an impact such that the angle of rebound is approximately equal to the angle of incidence and such that there is only an average linear momentum loss. After the impact particle A rebounds back into the air stream that is passing between the blades. The momentum of the particle is sufficient to overcome the drag between the blades, and the particle passes back out into the air stream down the louver face. Down the louver face is the direction from the inlet toward the blowdown parallel to the front wall. The speed of the particle away from the louver face decreases and the speed down the face increases because of the drag of the air stream down the louver face. The particle A may move six to eight inches down the louver face before the effect of the impact is no longer appreciable.

The pattern of the streamlines near the louver blades, Figure 3, was estimated by observing the behavior of very fine particles as they passed through the separator. These particles were all below one micron in diameter. The location of the air stagnation point on a blade was determined by the presence of a sharp pointed buildup of fine dust. The buildups were obviously at the stagnation point because they were fragile and fell off if the blade was tapped lightly.

The limit of the particle deflection before impact with the blade surface could be observed other than by particle paths. The blade face became brightly polished by the particle impacts. The end of the polished area of the blade was distinct and indicated the limit of particle deflection.

Particles were observed to pass between the blades because of "bad" impacts and because of too small an angle of incidence upon the louver face. A "bad" impact, used in contrast to a "good" impact, is an impact which is more inelastic than a "good" impact and which has an angle of rebound quite different from the angle of incidence. The "bad" impacts can be attributed to the irregular shape of the dust particles. Particle B Figure 2 is a representative particle which makes a "bad" impact. Particle B enters the separator and proceeds to the point of impact as did particle A. However, the particle makes a "bad" impact and rebounds with a greatly reduced momentum and with an unfavorable angle of rebound. As the particle passes back into the air stream between the blades it does not have enough momentum to overcome the drag and it is carried between the blades.

Some particles were observed to pass between the blades because of too small an angle of incidence upon the louver face. Particle C Figure 2 is an example of a particle that is incident upon the louver face with too small an angle for separation. Particle C is incident upon the blade surface in such a manner that after impact there is no tendency for it to pass out from between the blades. The drag of the air stream passing between the blades then carries the particle through the louver face.

A study of the overall performance of the louver showed that the blades near the blowdown or down stream end of the louver did not perform as well as the blades near the inlet. This is an inherent weakness of this type of separator. As the air stream moves toward the blowdown the dust concentration becomes higher, and thus the downstream blades have more particles incident upon them than do the upstream blades. Hence the last blades which have the largest number of particles to separate are the blades through which the largest number of particles pass.

There were a number of features of Matheson's apparatus that tended to amplify the non-uniform blade performance. The first and most important was a non-uniform air velocity through the louver face. The highest velocity was between the last few blades. Because of this high velocity, the performance of the blades near the blowdown was decreased. The high velocity between the blades is detrimental to performance because the higher the velocity between the blades the greater the drag tending to carry the particles through the louver. Thus the non-uniform flow through the louver face decreased the performance of the louver blades where good performance was most needed.

The nonuniform air flow was caused by the shape of the louver housing both in front of and in the rear of the louver face. The wall in the rear of the louver was so placed that it obstructed the flow through the upstream blades more than that through the down stream blades. The inlet cross section area of Matheson's apparatus was six square inches, and the blowdown cross section area was two square inches. Hence for blowdowns of less than thirty per cent there would be a lower velocity and higher pressure in the blowdown duct than in the inlet duct. This higher pressure in the blow-down section of the separator caused a higher pressure in front of the blades near the blowdown end of the separator than in front of the blades near the inlet. Thus more air was forced through the last blades of the separator.

When the blowdown air flow was about five per cent, the air stream in the blow down end of the separator was found to bend gradually before passing between the blades. The bending air stream caused the particle paths to bend toward the louver face. As the particles bend toward the louver face, the angle of incidence upon the louver face becomes smaller and the particles have much less chance of being separated.

When the blowdown air flow was less than five per cent, an eddy filled the space in front of the louver face just upstream from the blow-down outlet. This eddy completely destroyed the orderly motion of the particles in front of the down stream part of the louver face. With particles traveling in random paths, a large number of the particles were incident upon the louver face in a manner such that separation was impossible.

The effectiveness of the down stream blades of the separator was also decreased by particle rebounds from the front wall of the separator. This front wall effect became more pronounced the shorter the distance between the louver face and the front wall. This effect is best explained by following a representative particle. A particle impacts a blade surface in the usual way and rebounds after a "good" impact. The particle rebounds with enough momentum directed across the air stream to carry it to the front wall. The particle impacts the front wall with a "good" impact and rebounds across the air stream again. The particle then is incident upon the louver face with an angle which makes separation difficult. All of the particles that were participating in this effect were large high inertia particles.

Conclusions from the preliminary studies.--The first conclusion was that any overlap (see Figure 2) of the straight blades was unnecessary. Any particle that impacts the blade surface behind the point of zero overlap will rebound with a momentum directed through the louver face and hence can not be separated. Therefore any overlapping portion of the blades does not aid separation but only restricts the flow of air between the blades.

It was concluded that the flat blade design does not develop the full capabilities of this type of separator. The blade design was poor in that the particles experienced the drag between the blades once before impact with the blade surface and again after impact. The drag after impact was especially bad because on impact the particles lose much of their momentum, and therefore, after impact their motion is strongly influenced by the drag. The drag after a "bad" impact was strong enough to carry the particles between the blades. Thus if the particles do not have sufficient momentum away from the louver face after impact they will pass through the louver.

From the preliminary studies it also became evident that the shape of the housing around the louver is of paramount importance. For good separator performance the housing must be so shaped that there will be the same air flow through each opening in the louver or possibly a decrease in air flow through the openings with distance down the louver face. In any case there should not be an increase in flow through the openings with distance down the louver face. In order to achieve this uniform flow through the louver face the velocity of the air stream in front of the louver face must be maintained constant from inlet to blowdown. The back wall and clean air outlet of the separator must be arranged so that they will maintain a uniform back pressure on the louver.

CHAPTER III

SEPARATOR DESIGN

The blade design.--To minimize the weaknesses of the flat blade design an effort was made to separate the region where the particles impact the blade from the opening between the blades. A more effective blade design would cause the particles to rebound into an air stream directed down the louver face and not between the blades. In this way if a particle made a "bad" impact it would not pass between the blades. This amounts to separating the action of the blade into two operations. First because of impacts and resulting rebounds the particles are moved across the air stream and away from the louver face. The second operation is to allow the air to pass between the blades without allowing any particles to pass. Apparently the second operation is all that is necessary to separate the particles. However, if the particles were not moved away from the louver face a very concentrated dust band would develop in front of the louver face and a particle after first approaching the louver face would pass very close to all remaining openings between the blades. Hence the number of opportunities for a particle to pass through the louver face would be increased.

Several blade designs were mounted in Matheson's apparatus and observed in operation. The blade shape which appeared to have the best performance is shown in Figure 4. To understand the operation of this blade design examine the path of a representative particle shown in Figure

4. The particle enters the separator along a straight line path in the direction of the inlet air stream. The particle is one that just misses the front tip of a blade. The particle does not deviate observably from its straight line path until after it passes the tip of the blade which it just misses. After the particle passes the front tip of the blade, it passes into the air stream that is directed between the blades. The drag on the particle deflects the path, but the particle continues by virtue of its own inertia until it completely crosses the stream passing between the blades. The particle then passes into the air that is flowing down the straight portion of the blade. As the particle approaches the inclined portion of the blade it feels the effect of the air stream that has curved out along the inclined portion of the blade. The particle, affected only slightly by drag from this air stream, continues and impacts the inclined portion of the blade. The particle rebounds back into the air stream that has curved out the inclined portion of the blade and then out into the main air stream down the louver face. The velocity of the particle away from the louver face decreases and the velocity down the face increases because of the drag of the main air stream. The particle may travel six to eight inches after the impact before the effects of the impact are no longer observable.

The streamline pattern near the louver blades is sketched in Figure 5. As before the stagnation points were determined by the location of fine dust buildups.

Figure 6 shows the pattern of the particle paths after impact with the inclined portion of the blades. The figure was obtained by photographing the pattern eroded into the glass top of the separator.

If the particle should make a "bad" impact with the inclined surface of the blade, it will not pass through the louver face but will rebound with small momentum into the air stream along the inclined portion of the blade. As a result of the "bad" impact the particle will be carried only a small distance away from the louver face. Particles which are deflected more than the average particle as they pass in front of the blade opening will impact the straight portion of the blade. After the impact such a particle will rebound into the air stream flowing down the straight portion of the blade. This air stream carries the particle to a second impact with the inclined portion of the blade. With enough deflection a particle could pass directly between the blades without an impact. No particles were observed that were deflected to this extent.

The louver housing design.--A louver housing was designed which would as nearly as possible give the same velocity between each of the louver blades and which would as nearly as possible keep the velocity of the main air stream down the louver face constant from inlet to blowdown. In order to explain the design of the louver housing it is necessary to define the variables which were the basis for its design. Inlet area is the cross section area of the inlet to the separator. Blowdown area is the cross section area of the passage in front of the end of the last blade in the louver. The frontal area of the louver face is the projected area of the louver face on a plane normal to the direction of the inlet air stream. The open area of the louver face is the sum of the areas of all the openings through the face. The areas of the openings are measured in a plane that will give the maximum area. The frontal area of a blade is the portion of the frontal area of the louver that is the contribution of the blade. The open area of a blade is the area of the opening after the blade. The design velocity between the blades is the inlet velocity times the ratio of the blade frontal area to the blade open area. Thus if a louver of constant ratio of blade frontal area to blade open area is operating at the design velocity between the blades the air velocity through the louver face is constant.

The blades shown in Figure 4 are designed so that the ratio of blade frontal area to blade open area is one for each blade. The object of the louver housing design was to keep the velocity of the air stream down the louver face constant from inlet to blowdown. This requires first that the blowdown area must be selected to correspond to the blowdown flow desired. For example if a blowdown flow of five per cent is desired the blowdown area must be five per cent of the inlet area. The blowdown area must be located so that the blowdown portion of the inlet air stream can proceed to the blowdown without changing direction. If a louver of constant ratio of blade frontal area to blade open area is to operate at the design velocity between the blades, the frontal area of the louver and the blowdown area must project and together form an area coincident with the inlet area. Otherwise the air stream down the louver face will change direction and speed before passing between the louver blades. Changes in direction or speed of the air stream down the louver face will cause a non-uniform pressure in front of the louver face. Such a pressure condition does not permit the same flow through each of the louver openings.

There are a number of designs for louver housings that fulfill the requirements for keeping the velocity of the air stream down the louver face constant. The two dimensional separator satisfies the requirements, but if it is desired to design for small blowdown flows the louver face must be very close to the front wall near the blowdown. This is undesirable because the front wall effect will be increased.

The conical separator with the louver face formed into the frustrum of a right circular cone fulfills the requirements for uniform air velocity down the louver face. In this design there is no front wall, but the front wall effect is still present. In the conical separator the dust particles will, after impact, cross the separator and impact the louver face diametrically opposite the initial impact. If the diameter of the cone is small enough and the particle momentum after impact high enough, the second impact will be at an angle of incidence upon the louver face such that separation will be difficult if not impossible. The conical separator has the advantage that the length of the blades decreases with distance down the face. Fewer particles are incident upon the shorter blades; hence the shorter blades tend to compensate for the larger number of particles that pass through a unit length of opening between the last blades.

A sector of a conical separator fulfills the requirements for uniform air velocity down the louver face and has the advantages of a conical separator.

The housing for the test separator was designed to approximate a thirty degree sector of a conical separator. Actually the cross section of the separator was an isosceles trapezoid rather than a circular sector.

The separator was designed to be a sector of a complete separator to facilitate particle path studies and so that the approximate characteristics of a large separator could be determined with a small blower and other test equipment. The separator was constructed with a trapizoidal cross section rather than a circular sector to facilitate fabrication.

The inlet area of the separator was 9.53 square inches, and the blowdown area was 0.573 square inches. Thus the design blowdown for the separator was 6.01 per cent. Simplified sketches of the separator are given in Figure 7. A photograph of the separator is given in Figure 8.

The outlet of the separator was placed at the upstream end of the louver so that the clean air makes a 180 degree turn in passing through the separator. The outlet was placed so that the low velocity and high back pressure would be in the rear of the last blades of the louver. This was to keep the flow between the last blades of the louver equal to or smaller than the flow through the upstream blades and thereby compensate for the inherent poor performance of the last blades. Thus the blowdown portion of the initial air stream passes down the front of the separator without changing speed or direction. The clean air continues in the direction of the inlet air stream without changing velocity until it reaches the louver face. On reaching the louver face, the clean air makes a 180 degree turn in passing through the louver and then passes behind the louver to the outlet.

A detailed cross section showing the constructional features of the separator is given in Figure 9. The top of the separator was plate glass, and glass windows were placed in the front wall so that the particle paths could be observed. The bottom of the separator was held in place with screws and wing nuts so that it could be removed for changes in the separator blade assembly. One half inch pipe stiffening bars were welded to the separator to give it rigidity. The housing was fabricated of 18 gage sheet steel by welding. The louver was a soldered assembly of 28 gage galvanized sheet steel.

CHAPTER IV

APPARATUS

The air system.--The apparatus built by Matheson served as the basic equipment for testing the separator. A large number of rearrangements and alterations were necessary to make the equipment meet new requirements. Figure 10 and Figure 11 show the layout of the equipment.

The air for the tests was supplied by a Servant seven stage blower driven by an electric motor. The only available location for the apparatus necessitated a twenty-three foot run of four inch outside diameter sheet steel duct to bring the air from the blower to the equipment. Air from the duct passed through a ninety degree elbow and a sixty inch length of standard three inch pipe. The air then passed through a thin plate orifice meter and into a 15.5 inch length of standard three inch pipe. At the exit from this length of pipe the dust was fed into the air stream. The three inch pipe was changed through a transition section to the two inch by three inch rectangular entrance to a venturi section. The venturi was to insure thorough mixing of the dust into the air stream. The two inch by four inch outlet of the venturi was changed by a transition section to the trapezoidal inlet cross section. Six inches of trapezoidal duct were provided in front of the inlet to the separator.

The clean air stream which made a 180 degree change of direction in passing through the separator passes from the separator through the trapezoidal outlet. The outlet cross section was changed by a transition section to a two inch by four inch rectangular duct. The air stream made a ninety degree turn in the horizontal plane, passed through a transition to a two inch by three inch duct, and made a ninety degree turn in the vertical plane before entering the dust collecting chamber. For the outlet from the dust chamber, a length of standard three inch pipe provided with an orifice meter was fitted into the side of the dust chamber at the bottom.

The blowdown air stream which flowed from the separator through a trapezoidal outlet passed through a transition to a one inch by two inch rectangular duct. The blowdown stream made a ninety degree turn in the vertical plane and passed into the blowdown dust collecting chamber. The outlet from the blowdown dust chamber was a length of one and one half inch standard pipe fitted with a metering orifice. For small blowdown flows a calibrated flowrator was attached to the outlet pipe.

The air flows were regulated by obstructing the blower inlet, by adjusting a globe valve in the outlet from the blowdown dust chamber, and by varying an obstruction in the inlet to the clean air dust chamber.

Flow meters.--Three orifice meters were incorporated in the test set up. The clean air orifice and the inlet air orifice were built by Matheson. The blowdown air orifice was rebuilt so that it would measure small flows. All of the orifices were located so that they would meter dust free air. The inlet air orifice was provided with a sixty inch run of straight pipe upstream and a 15.5 inch run down stream. It was considered that these lengths were sufficient to insure that the orifice coefficients published by ASME were applicable to the inlet air orifice within the degree of accuracy required for this work. This orifice was used as is explained in the appendix to calibrate the other two orifices. All of the orifices were bolted between screwed flanges and were provided with standard flange pressure taps one inch upstream and one inch down stream from the respective orifice faces. Up stream static pressure taps were provided for each orifice, and the air temperature was measured up stream of the inlet air orifice. The static and differential pressures were measured with U tube manometers filled with water. The design and calibration of the orifices are given in Appendix E.

For low blowdown flows the flow rate was measured with a calibrated flowrator. The flowrator was attached to the end of the outlet from the blowdown dust chamber. The range of calibration of the flowrator and the blowdown orifice overlapped and provided a check point on the calibrations.

Dust collection chambers and dust bags.--The dust collection chambers were cylindrical cans with flanged tops. The covers were connected to the ducts coming to the chambers and were secured to the flange by means of screws and wing nuts. The dust collecting bags were Electrolux Cleaner bags. The clean air bag was four Electrolux bags sewed end to end and the blowdown bag was only one bag. The bags were sealed in place by clamping the flanged metal and rubber mouth of the bag between the flange on the top of the collecting can and the cover for the can. The wing nuts and screws provided the pressure for the seal and made disassembly for weighing easy. The outlets from the chambers were fastened into the sides near the bottom.

Dust feed.--A dust feeder, Figure 12, with a wide range of rates of feed was designed and built. The rate of feed ranged from 2.72 grams per minute to 255 grams per minute. The feeder was essentially a hopper closed at the bottom by a vibrating trough. The rate of feed was varied by adjusting the opening between the bottom of the hopper and the trough. The dust from the trough fell into a second hopper which opened at the bottom into an air injector. The injector, operated by compressed air, picked up the dust from the trough and some air from the room and injected them into the air stream entering the separator.

With the dust used for the experiment, the dust feeder provided a uniform and constant concentration. The feeder was consistent in its rate of feed so long as the rate setting was not changed, but it was time consuming to set the feeder at some desired rate of feed. A less sensitive means of changing the position of the trough would eliminate this difficulty. It is obvious that the feeder is not at all suitable for a dust that will not flow from a hopper.

Miscellaneous equipment.--A wet-dry bulb thermometer, a barometer, a balance sensitive to 0.1 grams and a stop watch were also used in conducting the tests.

CHAPTER V

PROCEDURE

When the apparatus was ready for a run the blower was started and the air flows set at the desired rates. The compressed air supply to the dust feeder was also turned on. The blower was run until the inlet air temperature became constant at about ten degrees above room temperature. This was to allow the dust bags to come to constant moisture content. The manometer readings for a desired flow were found by estimating the upstream density and then referring to the orifice calibration curves.

While the air temperature was increasing to the operating value, the dust feeder was set at the desired rate by measuring the time required for a known weight of dust to pass from the hopper. The feeder could be set without feeding the dust into the separator.

After the feeder was set and the air temperature had become constant, the blower was stopped and the empty dust bags were removed from the collecting chambers, weighed and replaced as rapidly as possible. It was not necessary to shut off the dust feeder air supply during the removal of the dust bags. Immediately after the dust bags had been replaced, the blower was started. While the air temperature was again stabilizing, a 68 gram sample of dust was weighed out in a beaker. This sample was used for each run because larger samples clogged the dust bags and appreciably changed the air flow rates during the run. The dust hopper was put in place empty and the vibrator started. At this time the flow rates were checked and readjusted if necessary. The right and left legs of the manometers measuring static and differential pressures on the orifices were read and recorded. If the flowrator was in use on the blowdown its reading replaced the manometer readings for the blowdown orifice. Also the air temperature, the wet and dry bulb room temperatures and the barometer pressure were read and recorded.

With this data taken the dust sample was poured into the dust feeder and at the same time the stop watch was started. The apparatus was watched closely for any irregularities during the run. As the dust emptied from the feeder the stop watch was stopped, and the length of the run recorded. The manometers measuring differential pressure on the orifices were again read and averaged with the readings at the start of the run.

The blowdown valve was then opened wide to blow out dust that tended to collect in the blowdown duct. At low blowdown air flows and especially at zero blowdown flow, it was necessary to use compressed air to blow out dust that collected in a corner of the blowdown section of the separator. For low total air flow rates it was necessary to increase the total air flow to blow out dust that collected in the clean air duct.

After all the dust that had settled out in the apparatus had been blown into the dust bags, the blower was stopped; and the dust bags were removed, weighed, emptied, weighed again, and returned as quickly as possible. The speed was necessary because the clean air dust bag on standing in the room about fifteen minutes would absorb about one gram of moisture. When the bags were again in place, the blower was started so that the bags would not absorb moisture before the next run.

The weights of dust collected in the clean air bag and in the blowdown bag were calculated. If the difference between the total dust collected and the dust input was five grams or more the run was repeated. A curve of the ratio of dust collected in the clean air bag to dust input versus the independent variable for the series of runs was plotted. If a run did not follow the trend of the data, it was repeated for verification.

Twenty runs were made. Runs one through ten were to determine the effect of the blowdown flow on dust separation. Runs eleven through fifteen were to determine the effect of initial dust concentration on dust separation. Runs sixteen through twenty were to determine the effect of initial air velocity on dust separation and pressure drop through the separator.

CHAPTER VI

DISCUSSION OF RESULTS

Effect of blowdown.--The effect of blowdown air flow on dust separation is shown in Figure 13. The point at which the performance of the separator breaks and decreases sharply is significant. This point is at about six per cent blowdown which is the blowdown for uniform velocity down the louver face. Thus as would have been predicted from the particle path studies, the performance of the separator is decreased if the velocity of the air stream decreases as it passes down the louver face.

It is interesting to examine Matheson's plot of the variation of dust separation with blowdown. (4) Matheson's apparatus when set for 22.5 degree face angle would have operated with a uniform velocity down the louver face at a blowdown of about thirty per cent. Matheson's extrapolated performance curve breaks at a blowdown of about thirty per cent as would be predicted. Thus it is concluded that the performance of the louver separator is decreased sharply if the ratio of blowdown air flow to total air flow is much less than the ratio of blowdown area to inlet area.

Effect of initial dust concentration.--The effect of initial dust concentration on dust separation is shown in Figure 14. The results show that the per cent of the dust that is separated is almost independent of the initial dust concentration. This is in agreement with Harwell (5).

The trend is to a slightly increased separation with increasing initial concentrations. This is probably due to collisions between the particles in the air stream.

Effect of initial air velocity.--The effect of initial air velocity on dust separation is given in Figure 15. This part of the test showed that to a large extent the performance of the separator is independent of the initial air velocity. The trend was to a slightly increased performance with decreased initial air velocities. In Matheson's test the trend was to improved performance at higher velocities. The fact that the performance is independent of initial air velocity is important in view of the variation of the pressure drop through the separator with initial air velocity. Figure 16 shows that the pressure drop through the separator increases rapidly with increasing initial air velocity. Thus at low initial air velocities the separator will separate the dust without absorbing the power that it would at high velocities.

It is felt that the range of initial air velocities tested covers the range that is important. Higher velocities than those tested are impractical because of the high pressure drop through the apparatus. Velocities lower than those tested would not transport the large dust particles.

The particle path observations also showed that the initial air velocity did not have a marked effect on the particle paths.

CHAPTER VII

PARTICLE SIZE DISTRIBUTIONS

The dust that was used throughout the tests was the Norton Company's Alundrum abrasive with a manufacturer's grain size classification of 240. This abrasive is aluminum oxide which has a specific gravity of about four.

Five dust samples were studied. The first was a sample of the input dust. The second and third samples were from the clean air bag and the blowdown bag with the separator operating at a low initial air velocity, and the last two samples were with the separator operating at a high initial air velocity.

The particle sizes were determined by the standard method for determining particle sizes by microscopic measurements. (6) A microscope slide was prepared from each sample. The slide was made by mixing the dust with a 20 per cent collodium 40 per cent butyl acetate mixture. A drop of the mixture was dropped on the surface of a beaker of water. The drop spread into a thin film thus giving an even dispersion of the dust particles. The film was then lifted from the surface of the water with a glass slide. After drying the slide was ready for study.

The slide was placed under a microscope fitted with a filar micrometer which had been calibrated with a stage micrometer. The size of 200 particles in each sample was measured. Every particle in a field of view was measured. Size frequency curves, Figure 17 through Figure 19, were plotted from the results. It was found that the dust particles were far from being uniform in size. The particle size ranged from about 120 microns to below three microns. Three microns was the approximate lower limit of particle size that could be measured with the microscope used.

The particle size frequency plots show that the separator was more effective on particles above 40 microns than on those below 40 microns. The most important fact that was brought out by the particle size determinations was that the separator was effective on particles as small as ten microns. This is evident because of the high frequency of occurence of particles of this size in the blowdown dust.

The mean weight diameter for the input dust was found to be 49 microns. The mean weight diameter was computed by the formula (7)

$$D_{mw} = \sqrt[3]{\frac{\Sigma n D^3}{\Sigma n}}$$

where: n = the number of particles in any size group

D = the mean diameter of the size group

Σ = summation

The mean weight diameter is the diameter of a particle such that if the weight of this particle is divided into the total weight of a sample the result will be the total number of particles in the sample. That is, it is the diameter of the particle of average weight. The mean weight diameter may be in error because the number of large particles that were measured was so small that the measurement of one or two more large particles would appreciably effect the mean weight diameter.

The mean diameter for the input dust sample was 25 microns.

CHAPTER VIII

IDEALIZED ANALYSIS OF PARTICLE PATHS

Particle paths near an opening through the louver.--In order to understand better the action of the separator an idealized analysis of the particle paths has been developed. This analysis is helpful in understanding the results of the tests and it may prove helpful in predicting the effect of other variables not studied at this time. The analysis is in two parts, the first being an analysis of the drag effect on a particle as it passes an opening between the blades, and the second being an analysis of a particle path after an impact with the inclined portion of a louver blade.

It is assumed that the dust particles are smooth spheres. The dust particle that just misses the tip of a blade is analyzed and it is assumed that the particle passes the tip of the blade with a velocity equal to the velocity of the air stream down the louver face. It is also assumed that the particle is traveling in the direction of the inlet air stream. As the particle passes the blade tip it passes into the air stream that is flowing between the blades. It is assumed that this air stream is of uniform velocity directed between the blades and is perpendicular to the inlet air stream. The assumptions about the air flow are admittedly only rough approximations.

Let x be the measure of the distance down the louver face in the direction of the inlet air stream. Let y be the measure of the distance through the louver face normal to x. Let the tip of the blade which the particle just misses be x = 0, y = 0. Let t = 0 be the time at which the particle in question passes through x = 0, y = 0.

The differential equation governing the x motion of the particle after t = 0 is

$$m \frac{dV_x}{dt} + C_d A \rho_a \frac{V_x^2}{2} = 0$$

with the initial conditions:

$$t = 0, \quad \begin{cases} V_x = V_{xa} \\ x = 0 \end{cases}$$

where: m = the mass of the particle

V_x = the x velocity of the particle

C_d = the coefficient of drag

A = the projected area of the particle

ρ_a = the density of the air

V_{xr} = the x velocity of the particle relative to the air and $V_{xr} = V_x$

V_{xa} = the velocity of the air stream down the louver face.

Because of the turbulence of the main air stream, the coefficient of drag for the particle is taken equal to 0.44, the value for fully developed turbulent motion of the air about the particle. This is in accordance with DallaValle. (8) Although the average velocity of the particle relative to the air over some short time interval may not be high enough to satisfy the criteria for fully developed turbulent motion of the air about the particle, the turbulent fluctuations of the air stream cause the instantaneous relative velocity between the air and the particle to be high enough for turbulent motion of the air about the particle. Hence if the air stream through which the particle is passing is itself in turbulent motion, the motion of the air about the particle will be turbulent regardless of the value of the average relative velocity between the air and the particle.

The differential equation governing the y motion of the particle after $t = 0$ is

$$m \frac{dV_y}{dt} - C_d A \rho_a \frac{V_{yr}^2}{2} = 0$$

with the initial conditions

$$t = 0, \quad \begin{bmatrix} V_y = 0 \\ y = 0 \end{bmatrix}$$

where: V_y = the y velocity of the particle

V_{yr} = the y velocity of the particle relative to the air and $V_{yr} = V_{ya} - V_y$

V_{ya} = the velocity of the air stream between the louver blades.

On solving the two differential equations and eliminating the parameter t, the equation of the particle path is

$$y = \frac{D\rho_p}{0.33\,\rho_a}\left\{\frac{V_{ya}}{V_{xa}}\left(e^{\frac{0.33\,\rho_a x}{D\rho_p}}-1\right) - \ln\left[\frac{V_{ya}}{V_{xa}}\left(e^{\frac{0.33\,\rho_a x}{D\rho_p}}-1\right)+1\right]\right\}$$

where: D = the diameter of the particle

ρ_p = the density of the particle

ρ_a = the density of the air.

The details of the solution are given in Appendix D.

It is important that velocity appears in the expression only as the ratio V_{ya}/V_{xa} which is the ratio of the velocity of the air down the louver face to the velocity of the air between the louver blades. This shows that the particle paths near the openings between the blades are independent of the initial air velocity becuase if the initial air velocity is changed, the velocity between the blades will be changed by the same ratio, and the ratio of the velocity down the louver face to the velocity between the blades will remain unchanged.

For a separator operating with uniform velocity down the louver face, the V_{ya}/V_{xa} ratio is determined by the ratio of blade frontal area to blade open area. Since the V_{ya}/V_{xa} ratio is the factor which determines the deflection of a given particle, the expression shows that the particle deflection may be decreased by lowering the ratio of blade frontal area to blade open area.

If as has been previously discussed a louver is operating with a decreasing velocity down the louver face, the velocity between the last blades is high and the velocity down the face in front of the last blades is low. Thus the last blades will have a high V_{ya}/V_{xa} ratio and a corresponding large particle deflection.

The particle path expression shows how the size of a particle affects its path. The paths of a five micron and of a ten micron particle have been plotted in Figure 20. The plot shows that the deflection of a ten micron particle is small and that the deflection of larger particles is even less than that for the ten micron particle. The small deflection of the ten micron particle apparently explains the effectiveness of the separator on particles as small as ten microns.

The curves of Figure 21 have been plotted in order to bring out more clearly how the size of a particle affects it deflection. The curves show the deflection, y, after 0.25 inches travel in the x direction for different particle sizes. Curves are also plotted to show the effect of different V_{ya}/V_{xa} ratios.

The expression for the particle paths indicates that particles of the same density diameter product should have the same particle paths.

Particle paths after impact with the inclined portion of the louvre blade.-- A similar analysis can be made of the particle paths after an impact with the inclined portion of the louver blade. As before the particles are assumed to be spheres. It is assumed that the particle in question travels in a straight line in the direction of the inlet air stream and impacts the inclined blade surface near the tip. Since the blade is at 45 degrees to the inlet air stream the assumed spherical particle will rebound with a velocity normal to the inlet air stream. Let x be the measure of the distance down the louver face in the direction of the inlet air stream. Let y be the measure of the distance normal to x away from the louver face. Let the point of impact be the point x = 0, y = 0. Let t = 0 be the instant of impact. Let V_{yo} be the velocity of the particle after impact. If it is assumed that the particle rebounds into an air stream of uniform velocity, V_{xa}, the differential equations governing the motion of the particle after t = 0 are

$$m\frac{dV_x}{dt} - C_d A \rho_a \frac{V_{xr}^2}{2} = 0$$

$$m\frac{dV_y}{dt} + C_d A \rho_a \frac{V_{yr}^2}{2} = 0$$

with the initial conditions

$$t = 0, \quad \left[\begin{array}{l} V_x = 0 \\ x = 0 \\ V_y = V_{yo} \\ y = 0 \end{array}\right.$$

where: V_x = the x velocity of the particle

V_{xr} = the x velocity of the particle relative to the air and $V_{xr} = V_{xa} - V_x$

V_{xa} = the velocity of the air stream down the louver face

V_y = the y velocity of the particle

V_{yr} = the y velocity of the particle relative to the air and $V_{yr} = V_y$

V_{yo} = the y velocity of the particle the instant after impact.

On solving the two differential equations and eliminating the parameter t, the equation of the particle path is

$$x = \frac{D\rho_p}{0.33\rho_a}\left\{\frac{V_{xa}}{V_{yo}}\left(e^{\frac{0.33\rho_a y}{D\rho_p}} - 1\right) - \ln\left[\frac{V_{xa}}{V_{yo}}\left(e^{\frac{0.33\rho_a y}{D\rho_p}} - 1\right) + 1\right]\right\}$$

The details of the solution are the same as for the solution of the paths near a louver opening.

In this expression for the particle paths the ratio V_{xa}/V_{yo} is important. If it is assumed that the particle before impact is traveling with the velocity of the air down the louver face, then the ratio V_{xa}/V_{yo} is the ratio of the speed of the particle before impact to the speed of the particle after impact. It seems reasonable that the ratio of the speed of the particle before impact to the speed of the particle after impact will be about the same regardless of the initial velocity. If this is true then the initial air velocity will not affect the particle paths after impact. Observations of the particle paths after impact did not reveal a marked change of the paths with changes in the initial air velocity.

The paths for four different particle sizes are plotted in Figure 22. A value of eight for the V_{xa}/V_{yo} ratio was arrived at for these curves.

This value gave particle paths which closely resembled the particle paths observed in the separator.

The V_{xa}/V_{yo} ratio is undoubtedly dependent upon the nature of the particles. Since the V_{xa}/V_{yo} ratio is one of the factors which determines how effectively the particles are moved away from the louver face, it is a factor which must be considered when an attempt is made to predict the effectiveness of the separator on some other dust. If the particles have a low V_{xa}/V_{yo} ratio the front wall effect will become important. If the particles have a high V_{xa}/V_{yo} ratio the particles will remain close to the louver face and have many opportunities to pass through a louver opening.

The limitations of this analysis of the particle paths must be kept in mind. First, the analysis is definitely only a first approximation, and therefore cannot give precise answers. Second, the analysis is dependent upon the turbulence of the air that is passing through the separator. If the air is not turbulent the coefficient of drag for the particles, C_d, is not a constant equal to 0.44 and the analysis breaks down.

CHAPTER IX

CONCLUSIONS AND RECOMMENDATIONS

Conclusions.--The most important conclusion that can be drawn from this investigation is that the performance of the separator can be maintained at low blowdown flows if the louver housing is designed so that the velocity of the air stream down the louver face is constant from inlet to blowdown. It was found that the uniform velocity of the air stream down the louver face was necessary to insure a uniform flow through the louver face. A nonuniform flow through the louver face was detrimental to the separator performance because the increased velocity between the last blades of the louver enabled more particles to pass between these blades. The decreased velocity between the first blades of the louver did not decrease the number of particles passing between these blades enough to compensate for the increased number of particles passing between the last blades.

It was found that the straight flat blade design did not develop the full capabilities of this type of separator. The flat blade design is such that the particles impact the blade surface in the region where the air is passing between the blades. Thus after impact with the blade surface the particles have a low momentum and are easily carried between the blades. The new blade design overcomes these difficulties by separating the region of particle impact from the region where the air is passing between the blades.

Performance tests of the redesigned separator showed that the per cent of the dust separated was essentially independent of the initial dust concentration. The tests also showed that the per cent of dust separated was essentially independent of the initial air velocity. This conclusion was supported by the fact that the observed particle paths were not changed to a great extent by changes in the initial air velocity and by the fact that the analysis showed the particle paths to be independent of the initial air velocity.

It was found that at low initial air velocities the performance of the separator could be maintained with a total pressure drop through the separator of less than one half inch of water.

Particle size studies on dust samples from the clean air and from the blowdown showed that the separator was effective on dust particles as small as ten microns. The effectiveness of the separator on particles of this size was supported by the analysis of the particle paths.

The approximate analysis of the particle paths also showed how the ratio of blade frontal area to blade open area, the size of the blade opening, the particle size, the ratio of particle density to air density, and the ratio of the speed of the particle before impact with the blade surface to the speed of the particle after impact might affect the performance of the separator.

Recommendations.—The recommendations for future work on this type of separator hinge around the observations of how a few particles are able to get through the louver face of the redesigned separator. It is felt that a large portion of the particles are passing through the louver face because of the effects of the bottom and top walls of the separator. The air near the wall is moving slower than the air away from the wall. Thus it is easier for the low velocity air to turn through the louver. Hence near the wall the ratio of the velocity through the blades to the velocity down the face is high with the corresponding increased particle deflections. The impacts of the particles with the bottom and top walls account for part of the bottom and top wall effects. A full conical separator would eliminate all the top and bottom wall effects because the separator blades would be continuous.

Another portion of the particles that were passing into the clean air were passing through a small crack between the glass top of the separator and the ends of the louver blades. The crack was small but still large enough to pass particles of the size used in the test. A fact that supports this is that if the louver blade assembly was removed from the separator and replaced, the data was not reproduced even though there were no changes. A removal of the louver blade assembly accounts for the discrepancy between run 5 and run 16.

It is recommended that a full conical model be built and tested. It is felt that the inlet would have to be at least ten inches in diameter for the test to be fair. On a smaller model designed for five per cent blowdown or less the diameter near the blowdown would be small enough for the particles to rebound across the diameter of the separator and impact the opposite side of the louver with little chance of separation.

A number of particles were observed passing through the present louver because of the front wall effect. As the other features of the separator become more efficient the effect of the front wall becomes more important. It is recommended that an attempt be made to eliminate the front wall effect by making the angle of the inclined portion of the blade only large enough so that upon rebounding the large particles will have only enough momentum to carry them once across the separator. Thus at the blowdown end of the separator the inclined portion of the blades would be at a small angle to the inlet air stream. The required angle could be approximated by the use of an analysis of the particle paths after impact.

APPENDIX A

LIST OF SYMBOLS

LIST OF SYMBOLS

A	Projected area of a dust particle
C	Coefficient of discharge
C_1	Constant of integration
C_2	Constant of integration
C_3	Constant of integration
C_4	Constant of integration
c_1	Inlet air dust concentration
c_2	Clean air dust concentration
D	Particle diameter
D_{mw}	Mean weight diameter
D_1	Pipe diameter
D_2	Orifice diameter
G_1	Rate of dust flow in initial air
G_2	Rate of dust flow in clean air
h_d	Pressure drop through separator
h_{s1}	Upstream static pressure, inlet air orifice
h_{s2}	Upstream static pressure, clean air orifice
h_{s3}	Upstream static pressure, blowdown orifice
h_1	Differential pressure, inlet air orifice
h_2	Differential pressure, clean air orifice
h_3	Differential pressure, blowdown orifice
K	$\frac{C_d A \rho_a}{2m}$

m	Mass of a particle
n	Number of particles
T_a	Temperature of the air in the separator
T_d	Dry bulb room temperature
T_w	Wet bulb room temperature
t	Time
V_x	x velocity of a particle
V_{xa}	x velocity of the air
V_{xr}	x velocity of a particle relative to the air
V_y	y velocity of a particle
V_{ya}	y velocity of the air
V_{yo}	y velocity of a particle the instant after an impact
V_{yr}	y velocity of a particle relative to the air
w	Mass rate of air flow
w_1	Mass rate of air flow, inlet air orifice
w_2	Mass rate of air flow, clean air orifice
w_3	Mass rate of air flow, blowdown orifice
x	Distance down the louver face
y	Distance normal to x
β	Ratio of orifice diameter to pipe diameter
ρ_a	Density of the air in the separator
ρ_p	Density of a dust particle
ρ_1	Density of air upstream from an orifice
Σ	Summation

APPENDIX B

FIGURES

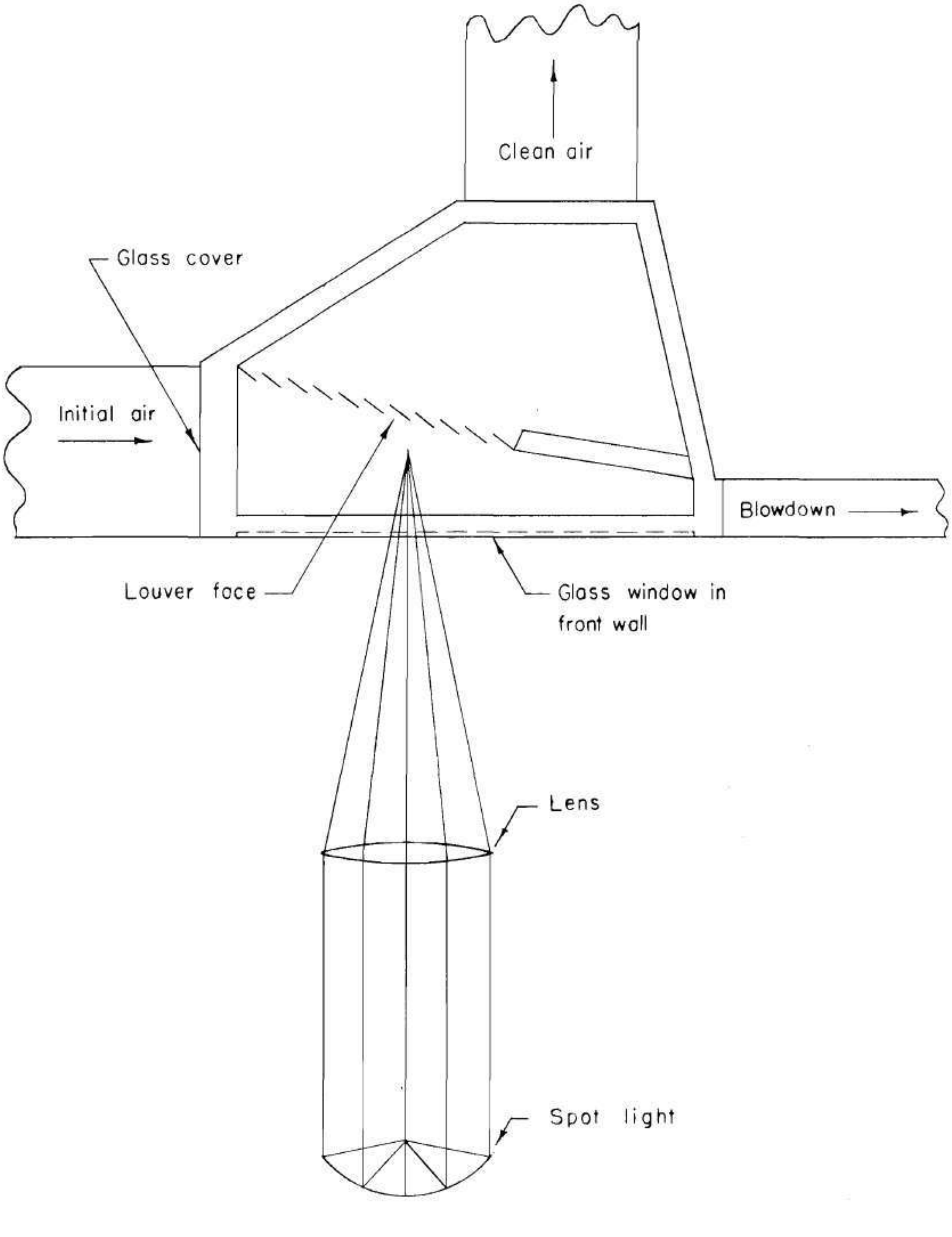

FIGURE 1

TWO DIMENSIONAL LOUVER SEPARATOR WITH MODIFICATIONS FOR PARTICLE PATH OBSERVATIONS

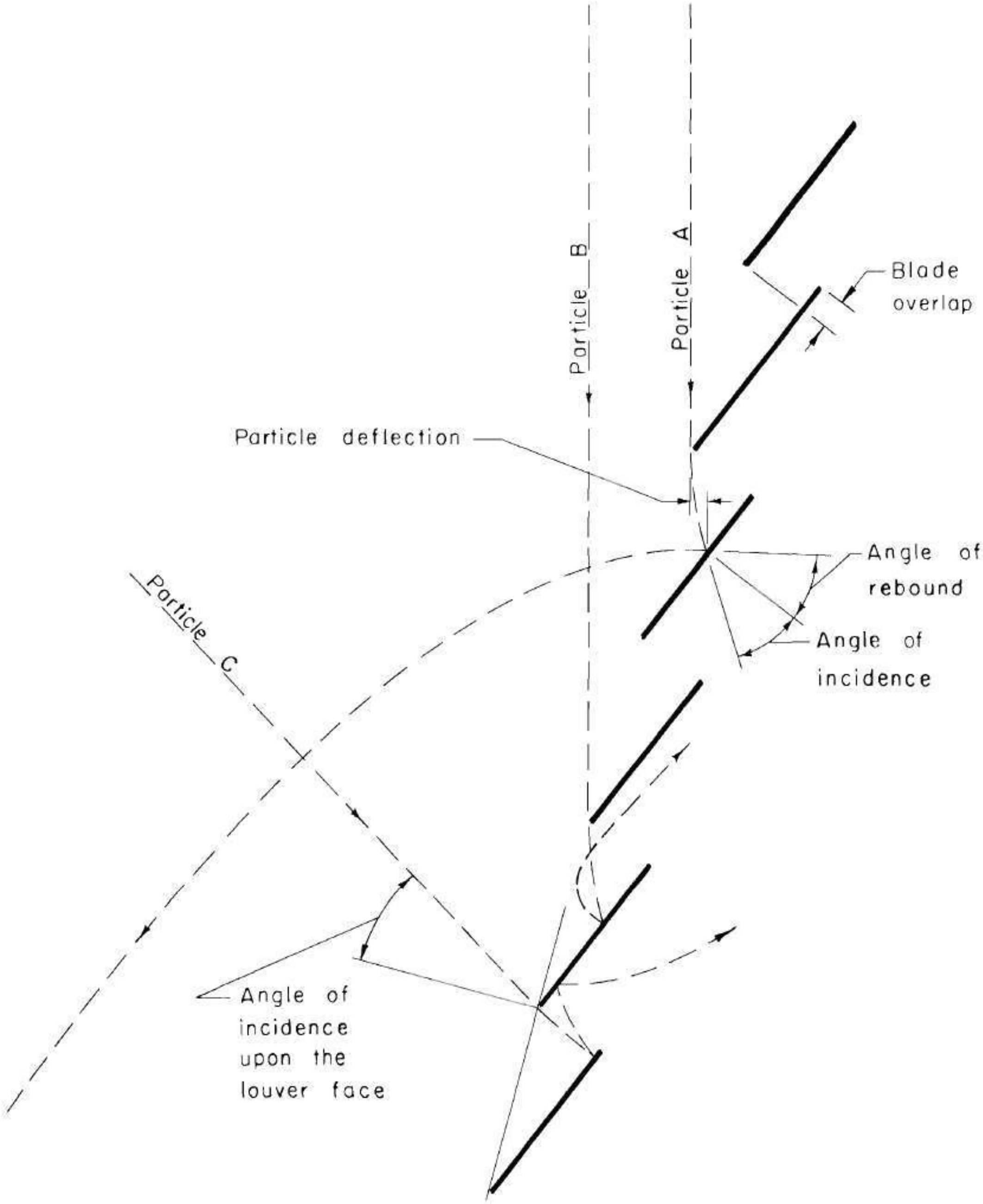

FIGURE 2
SKETCH OF REPRESENTATIVE PARTICLE PATHS IN THE STRAIGHT BLADE SEPARATOR

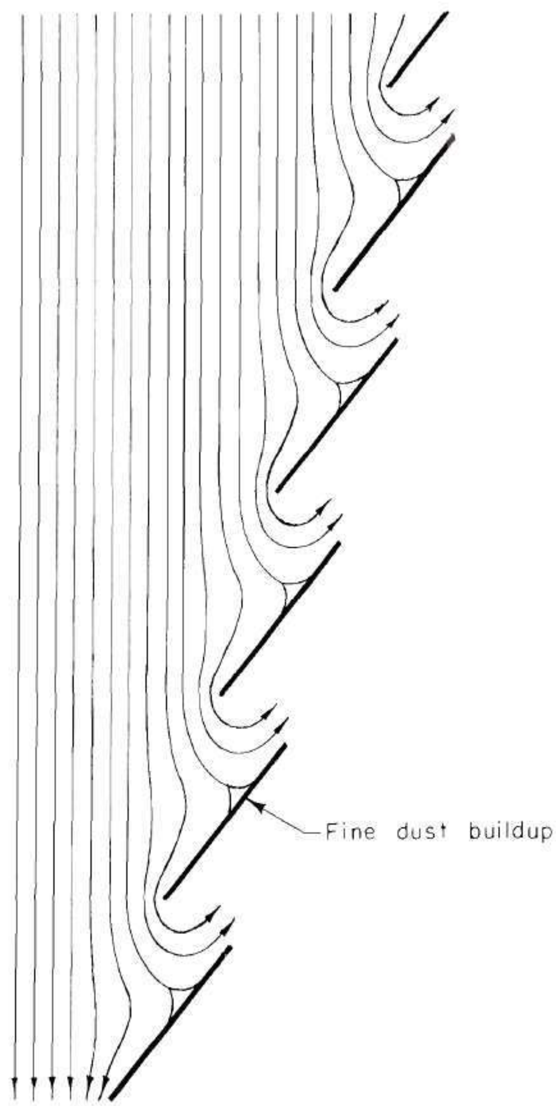

FIGURE 3
SKETCH OF STREAMLINES NEAR
STRAIGHT LOUVER BLADES

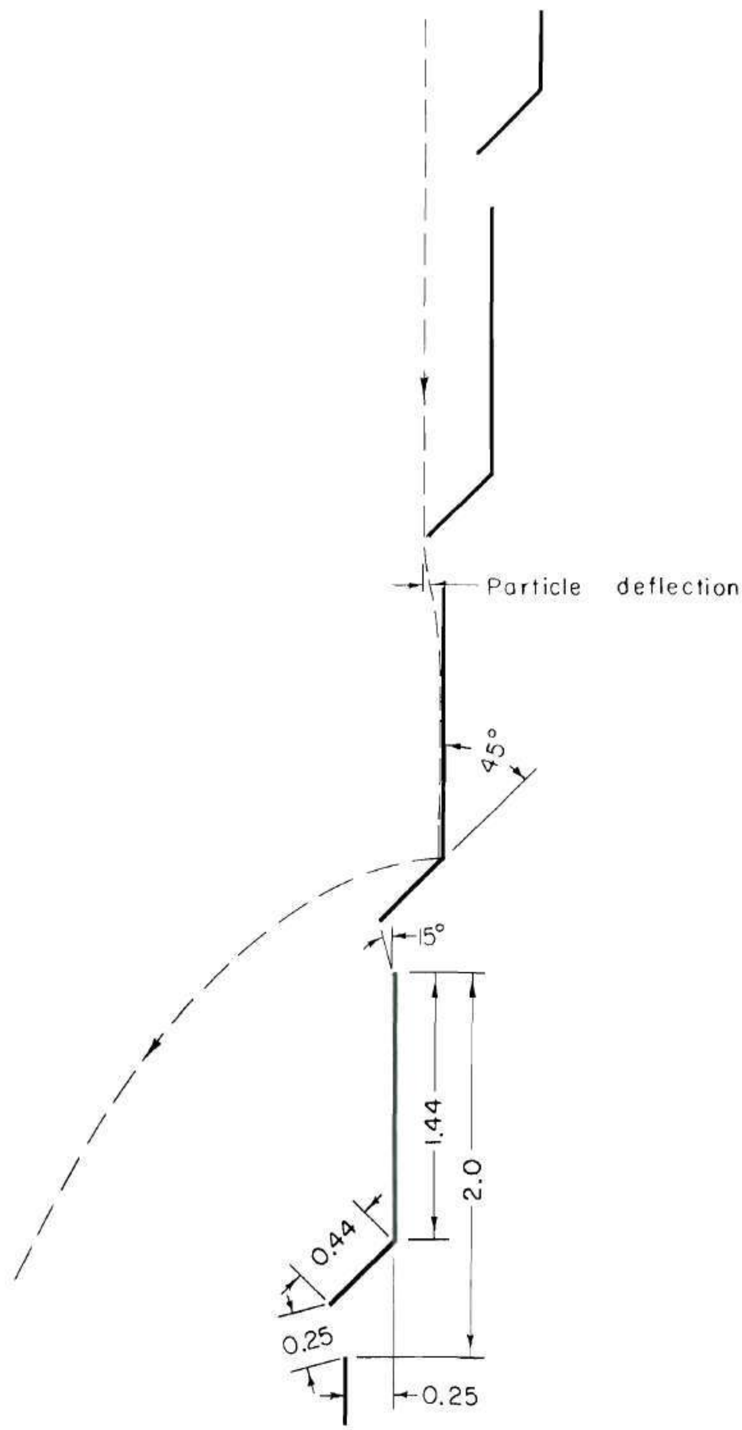

FIGURE 4
BLADE DESIGN AND SKETCH OF A
TYPICAL PARTICLE PATH

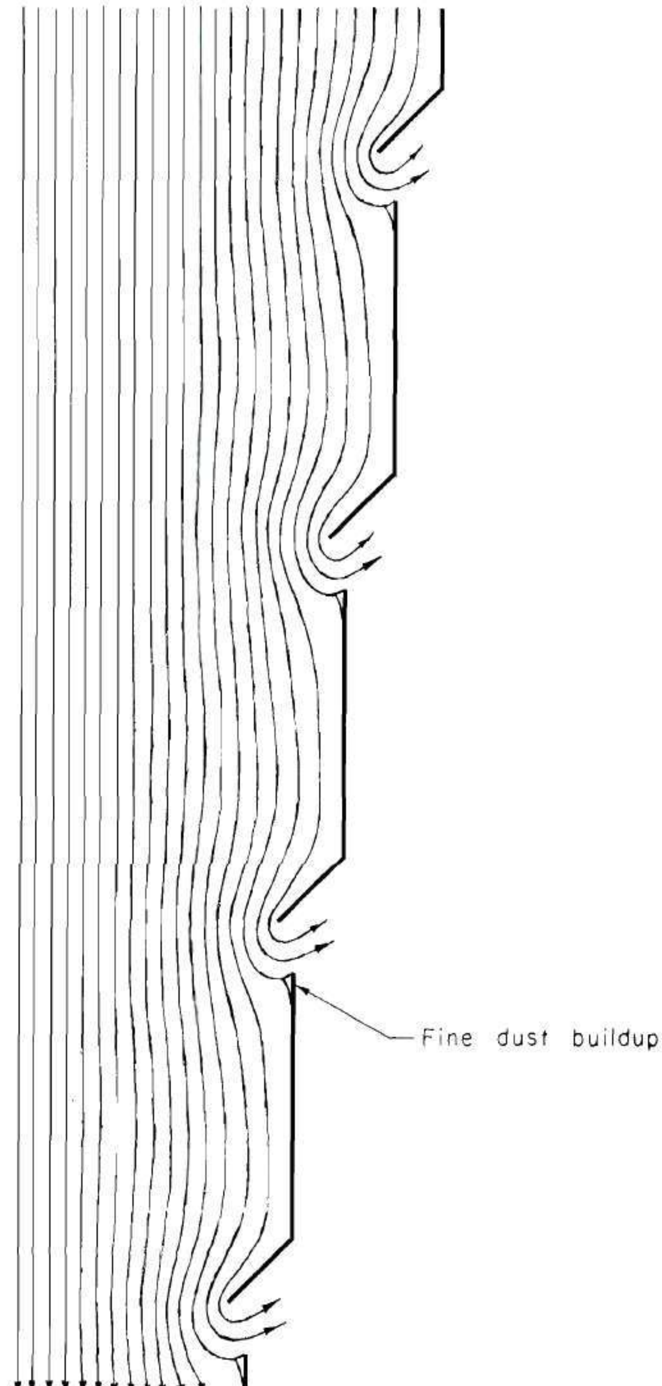

FIGURE 5
SKETCH OF STREAMLINES NEAR
LOUVER BLADES

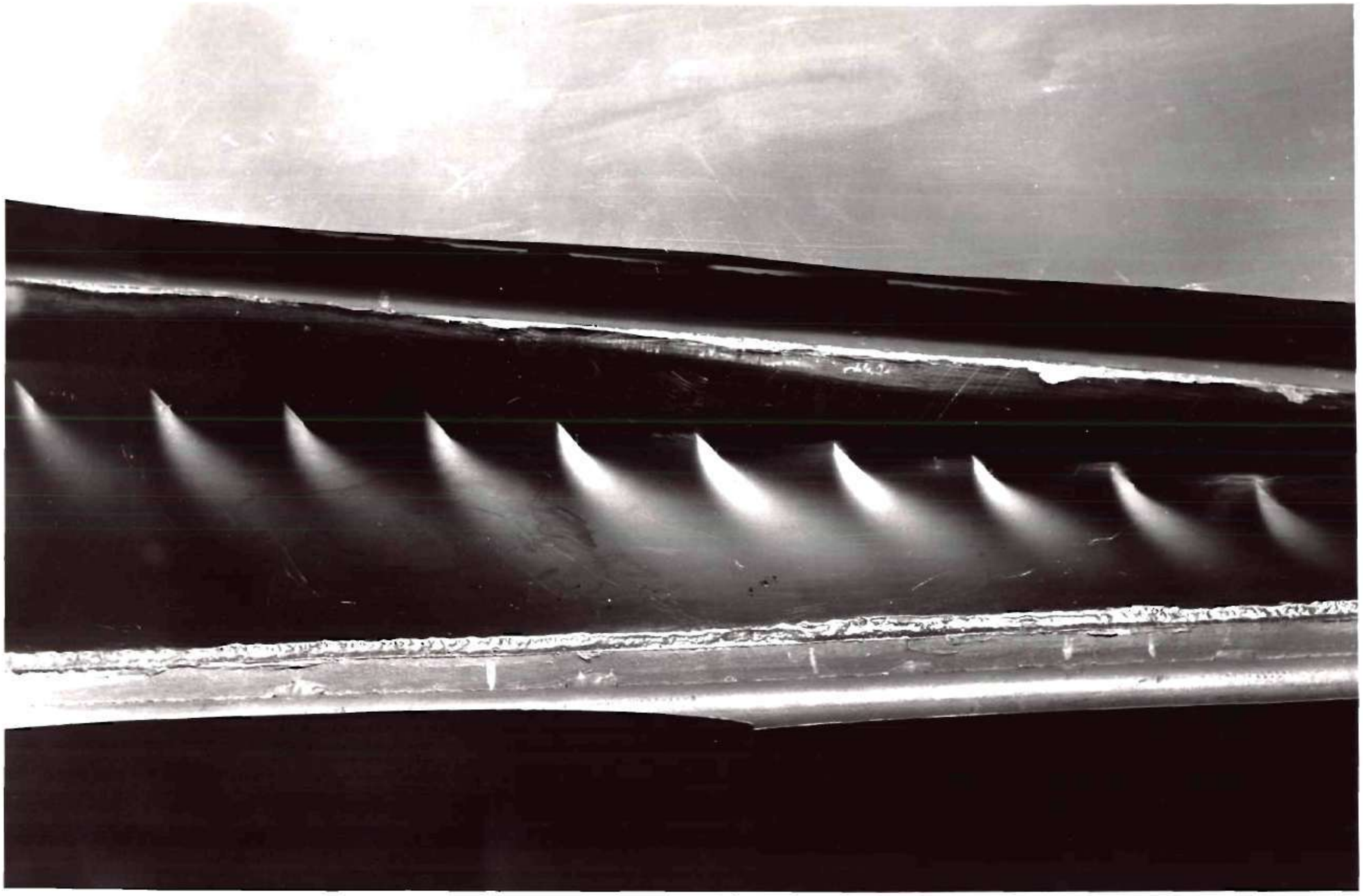

FIGURE 6
PHOTOGRAPH OF THE PATTERN ERODED INTO THE GLASS TOP OF THE SEPARATOR

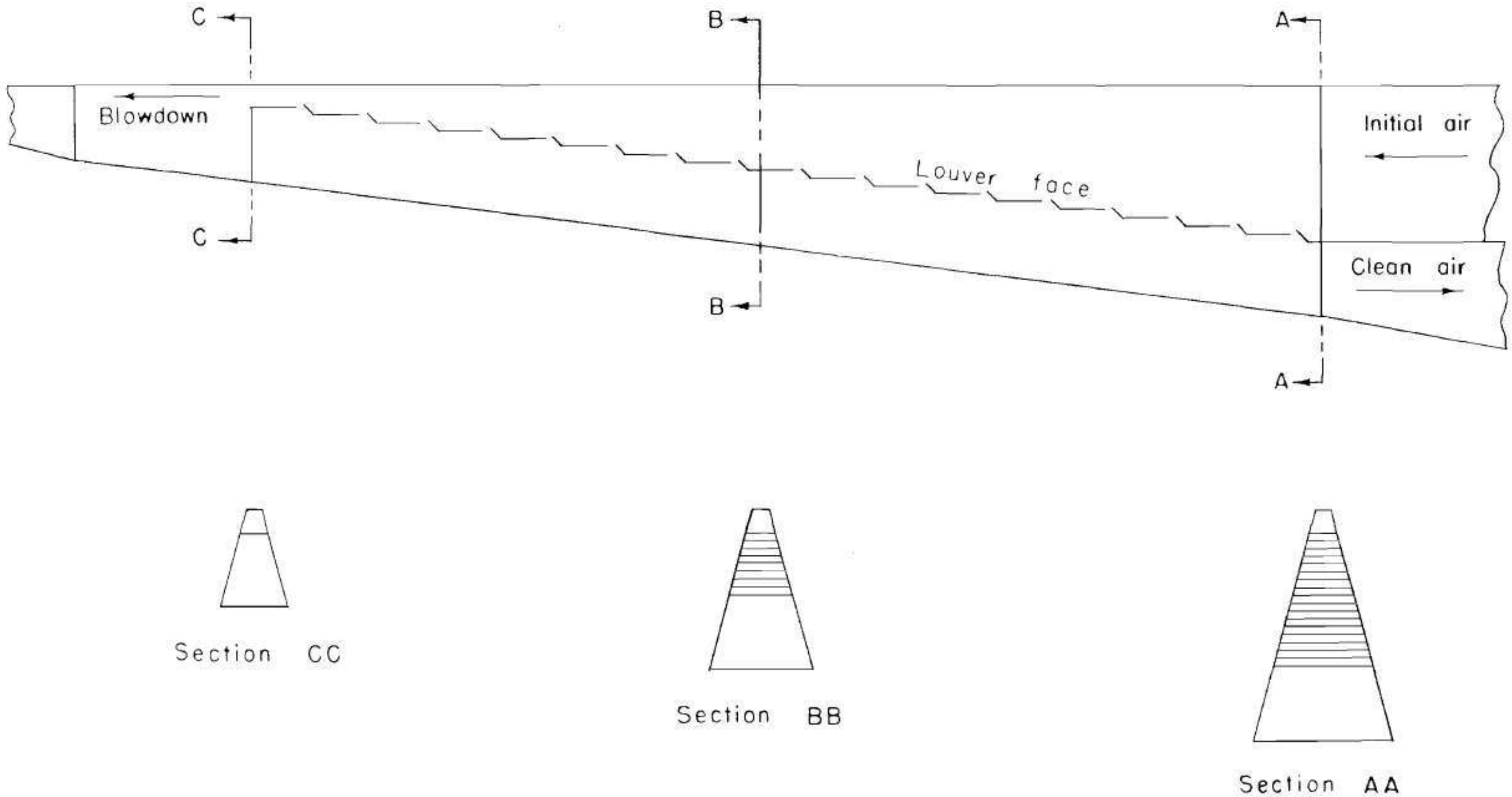

FIGURE 7
SIMPLIFIED SKETCH OF THE SEPARATOR

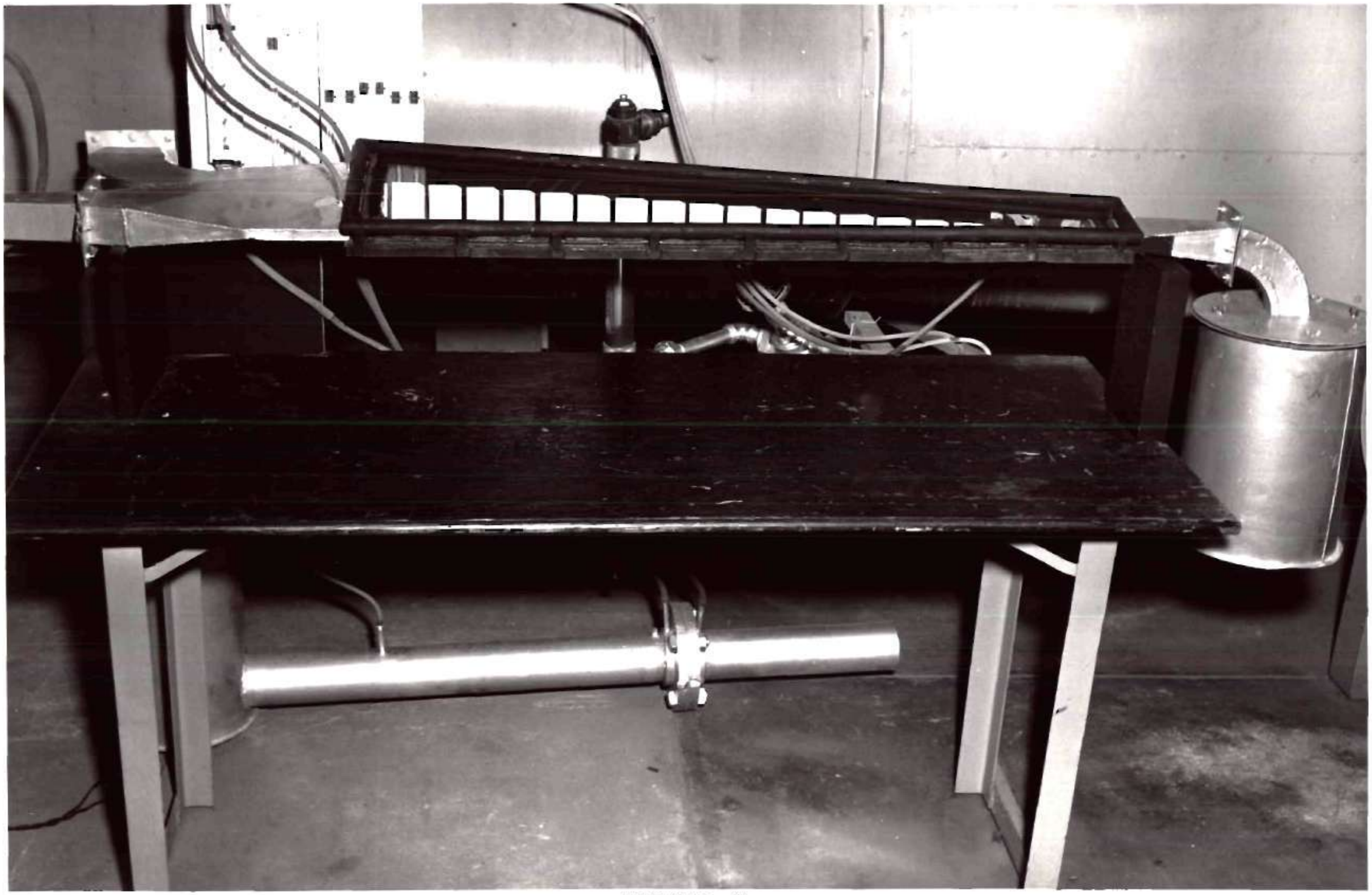

FIGURE 8
PHOTOGRAPH OF THE SEPARATOR

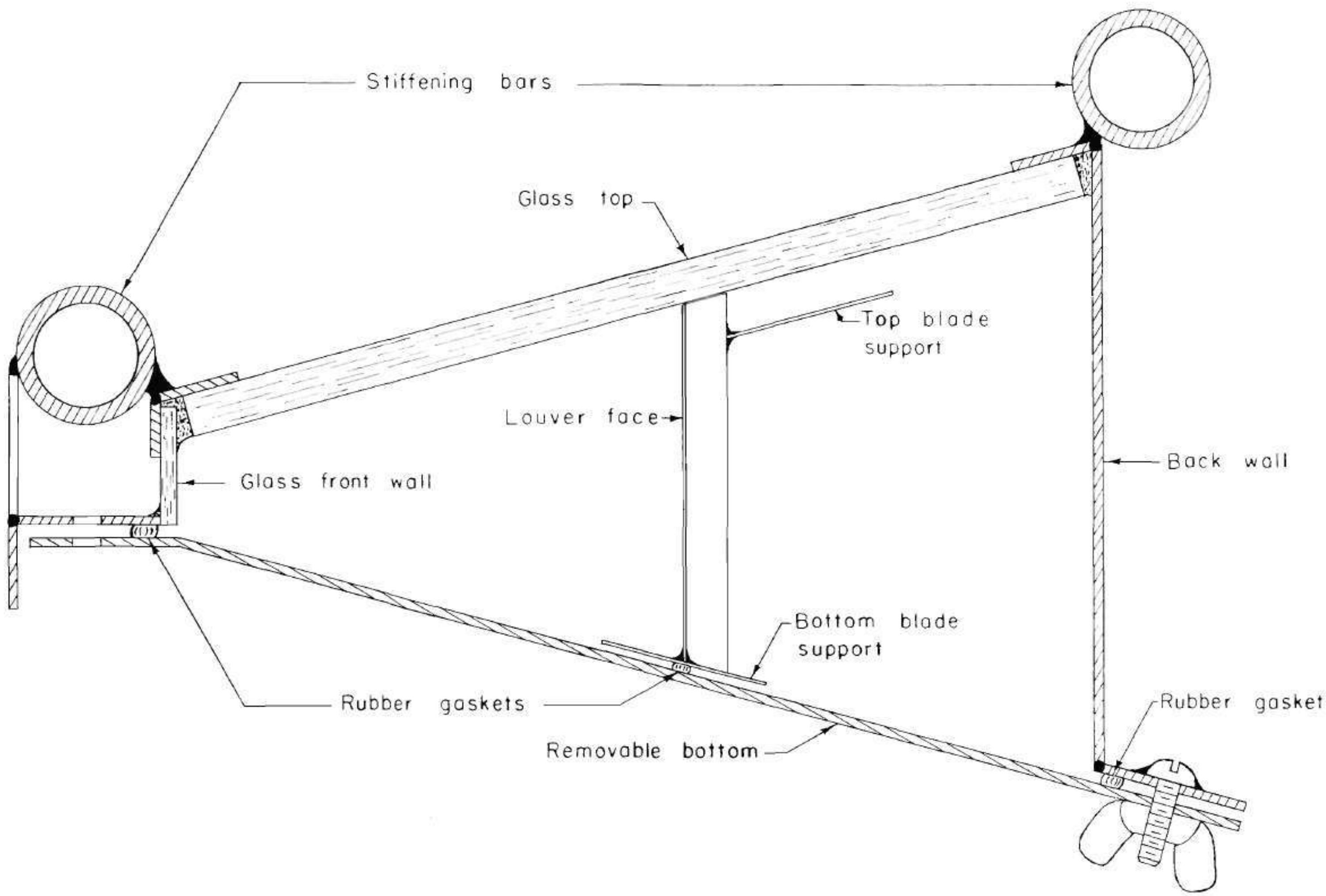

FIGURE 9
DETAIL CROSS SECTION OF THE SEPARATOR

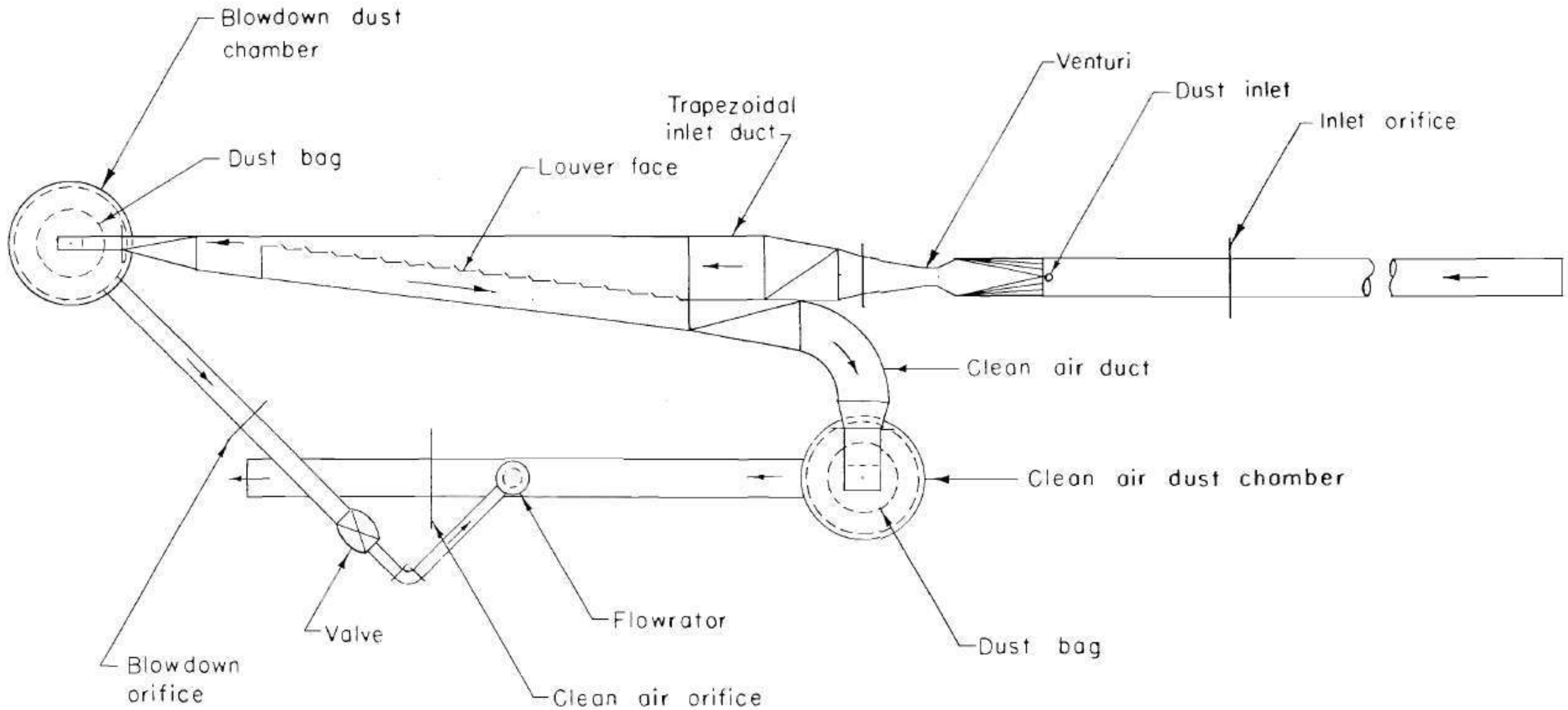

FIGURE 10
SKETCH OF APPARATUS FOR
THE SEPARATOR TEST

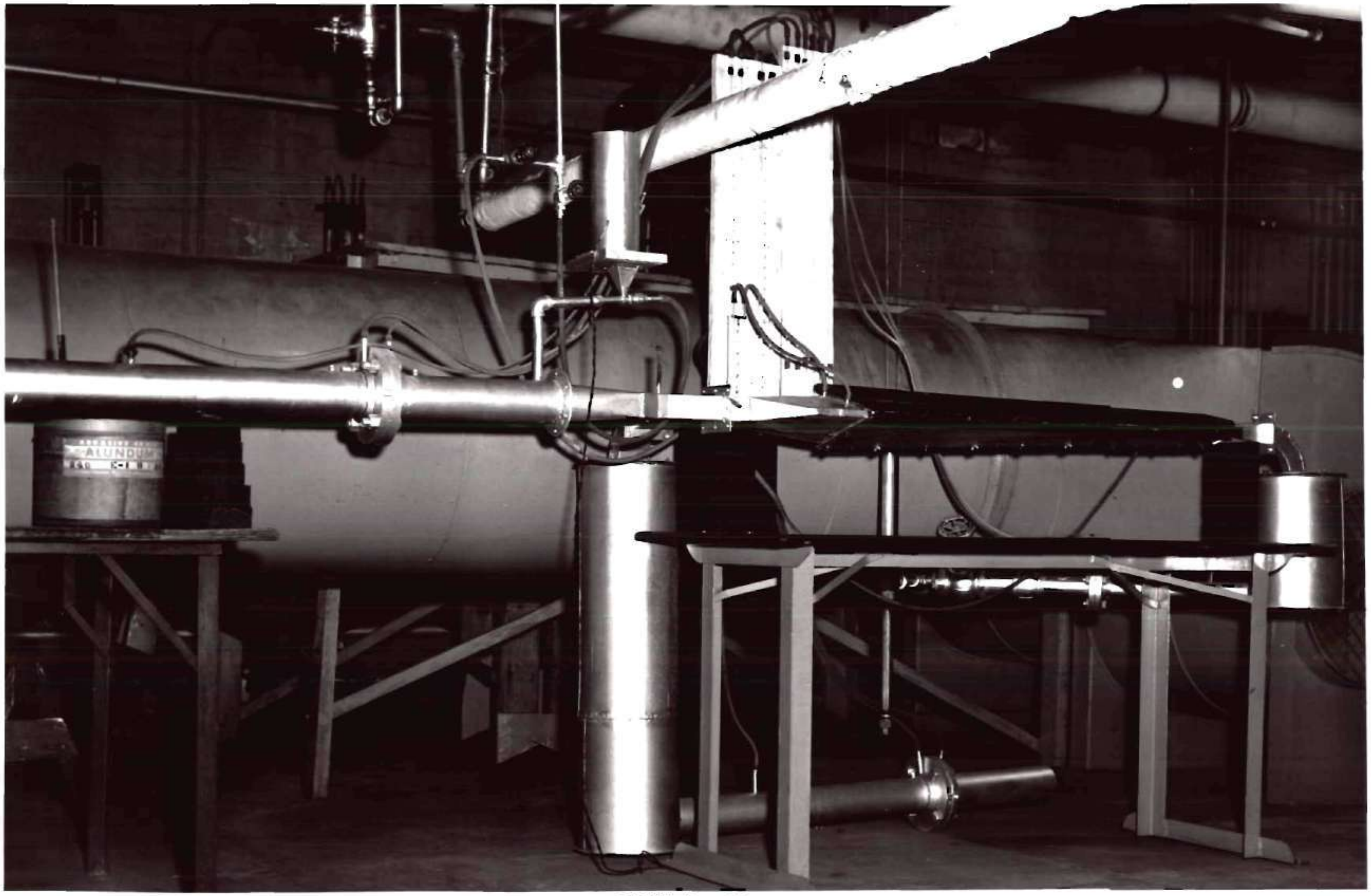

FIGURE 11
PHOTOGRAPH OF APPARATUS FOR THE SEPARATOR TEST

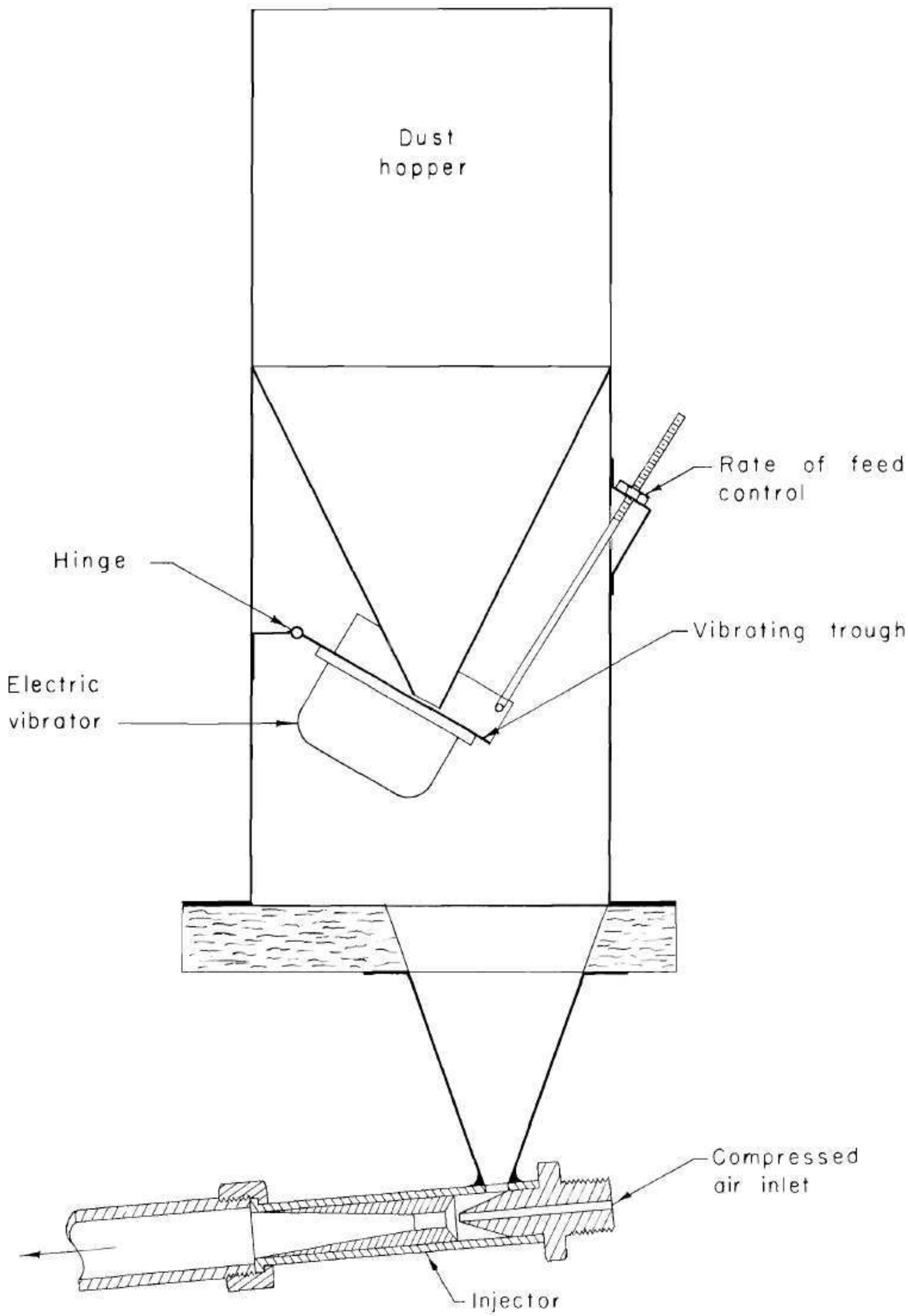

FIGURE 12
SKETCH OF THE DUST FEEDER

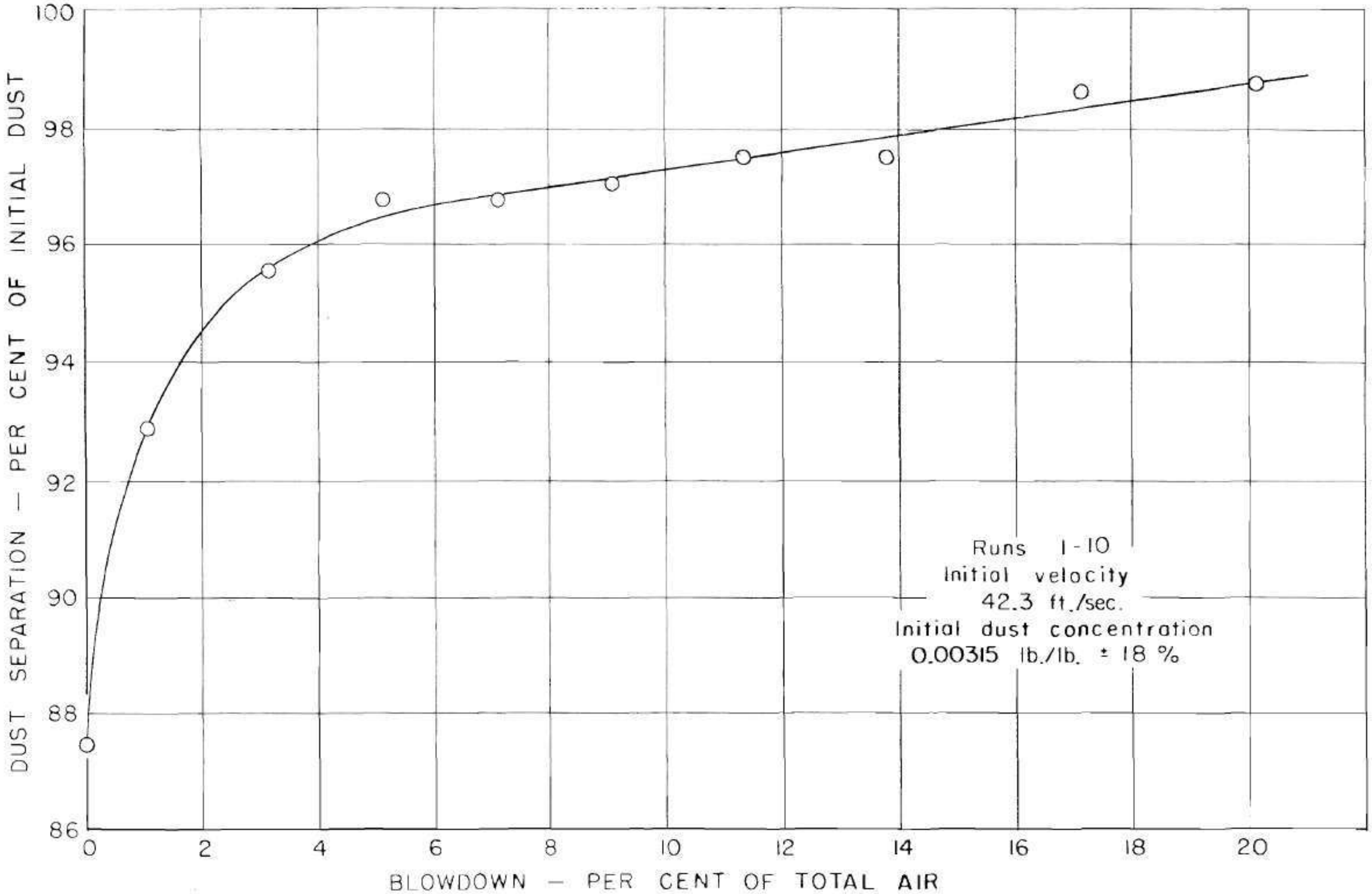

FIGURE 13
EFFECT OF BLOWDOWN ON DUST SEPARATION

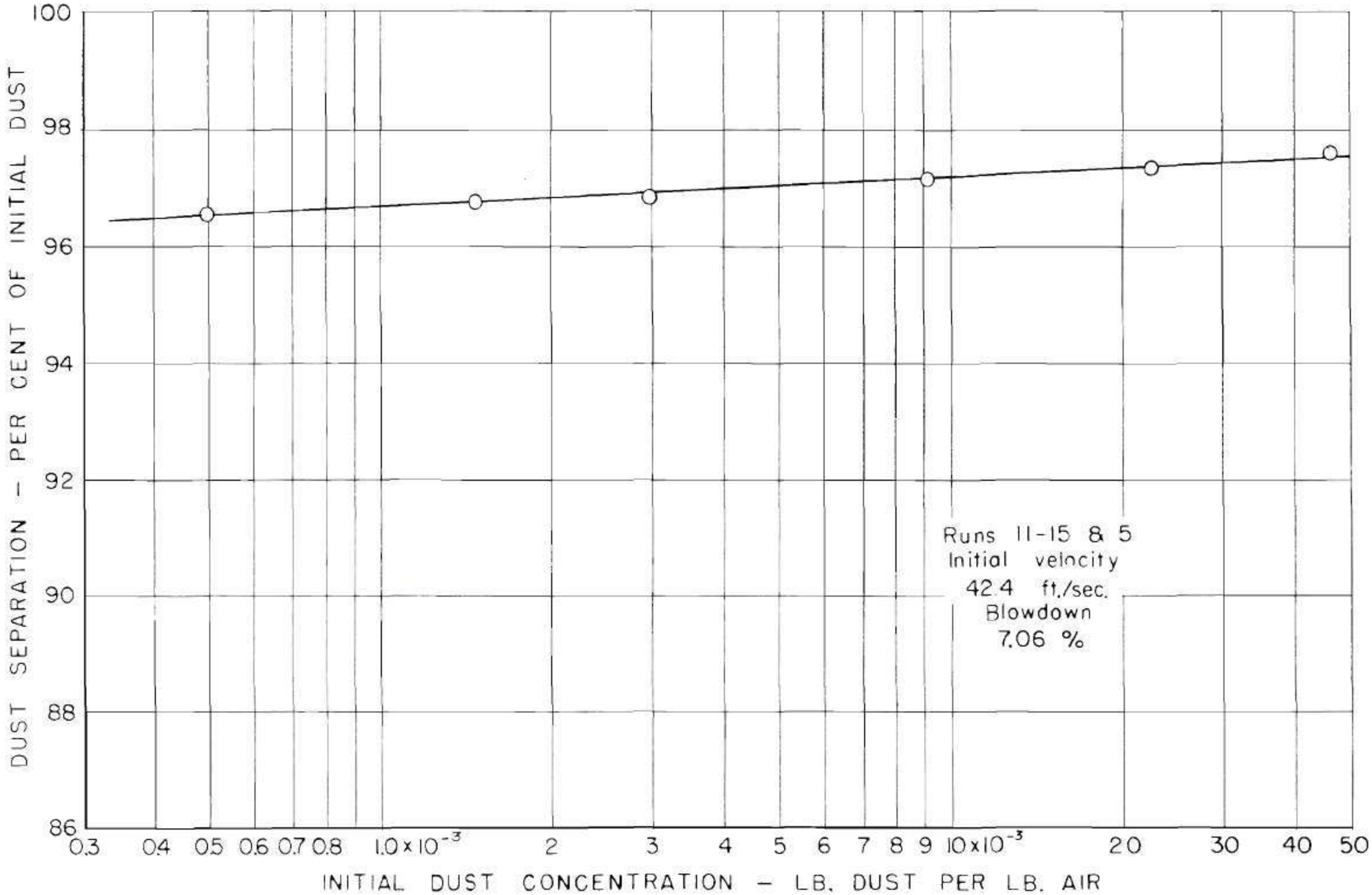

FIGURE 14
EFFECT OF INITIAL DUST CONCENTRATION
ON DUST SEPARATION

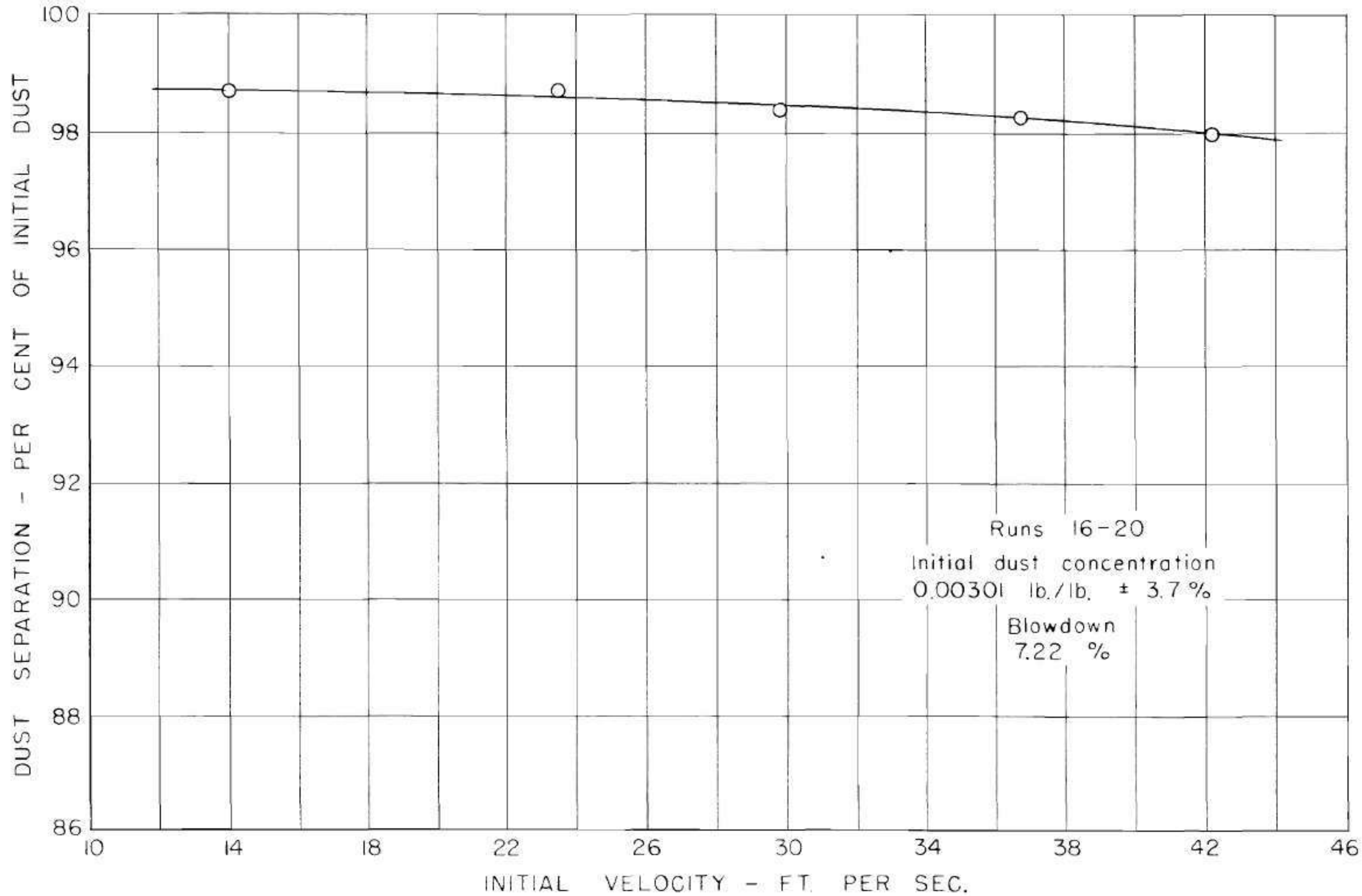

FIGURE 15
EFFECT OF INITIAL AIR VELOCITY
ON DUST SEPARATION

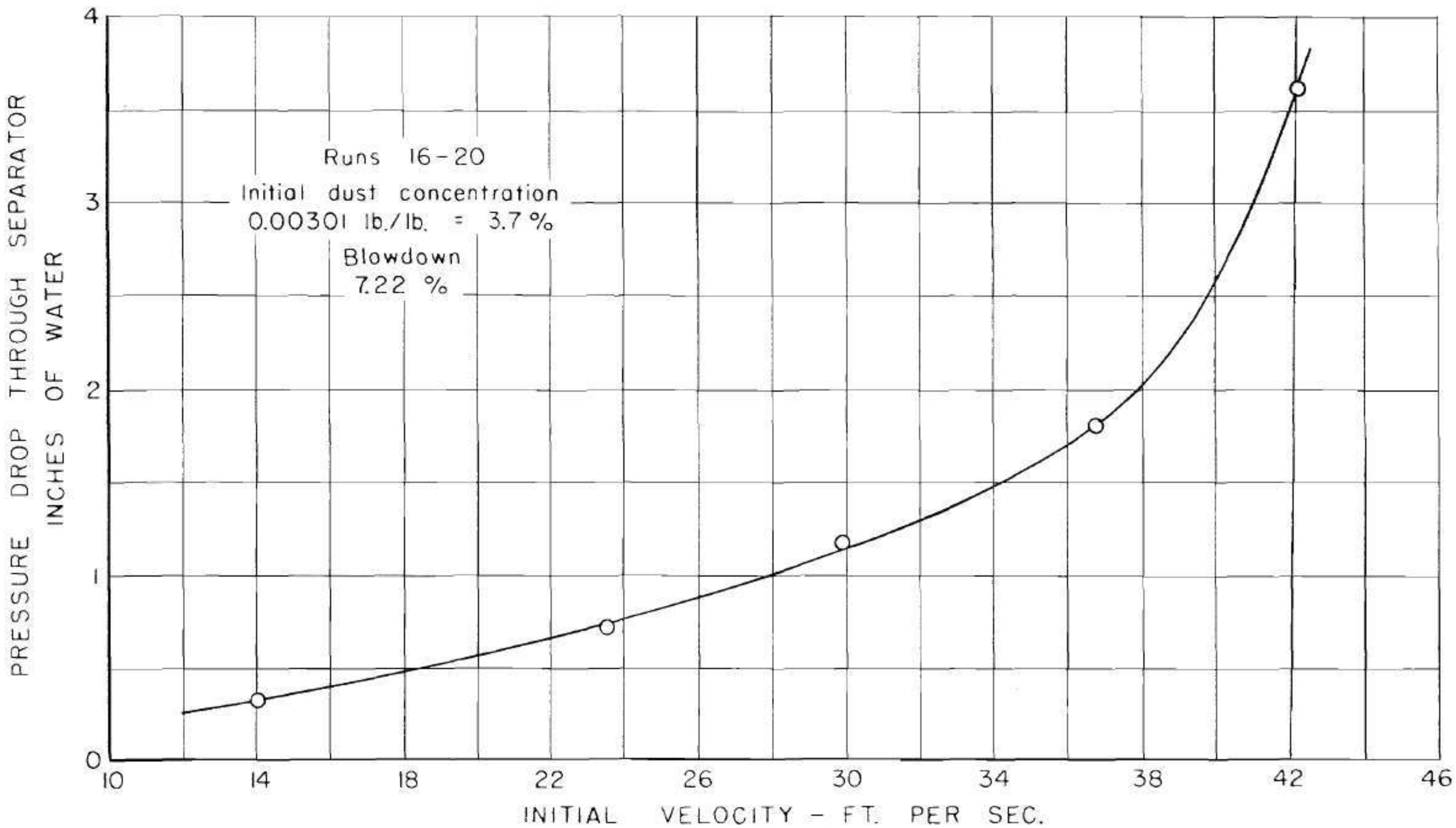

FIGURE 16
EFFECT OF INITIAL AIR VELOCITY
ON PRESSURE DROP THROUGH THE SEPARATOR

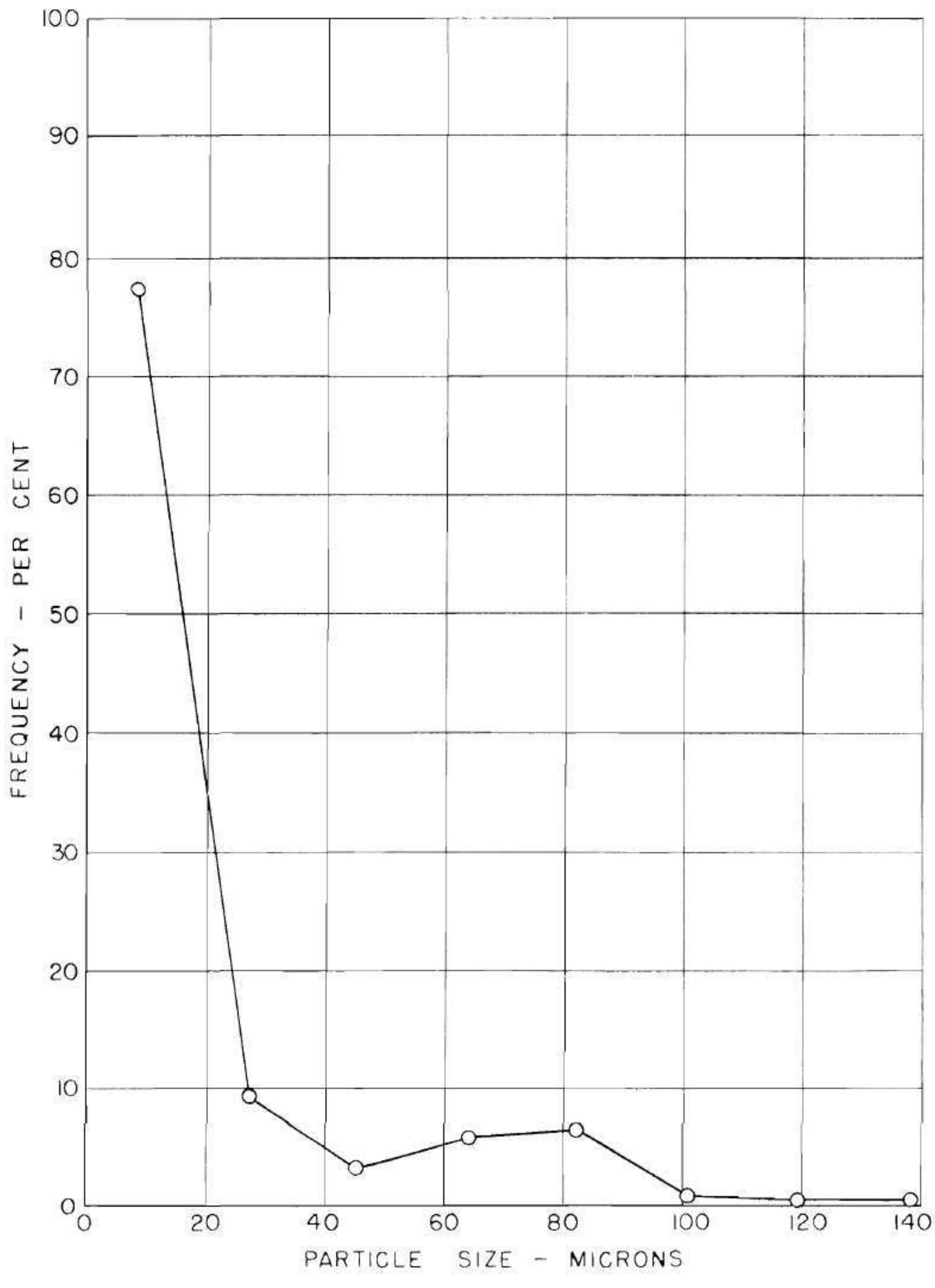

FIGURE 17
PARTICLE SIZE DISTRIBUTION
INITIAL DUST

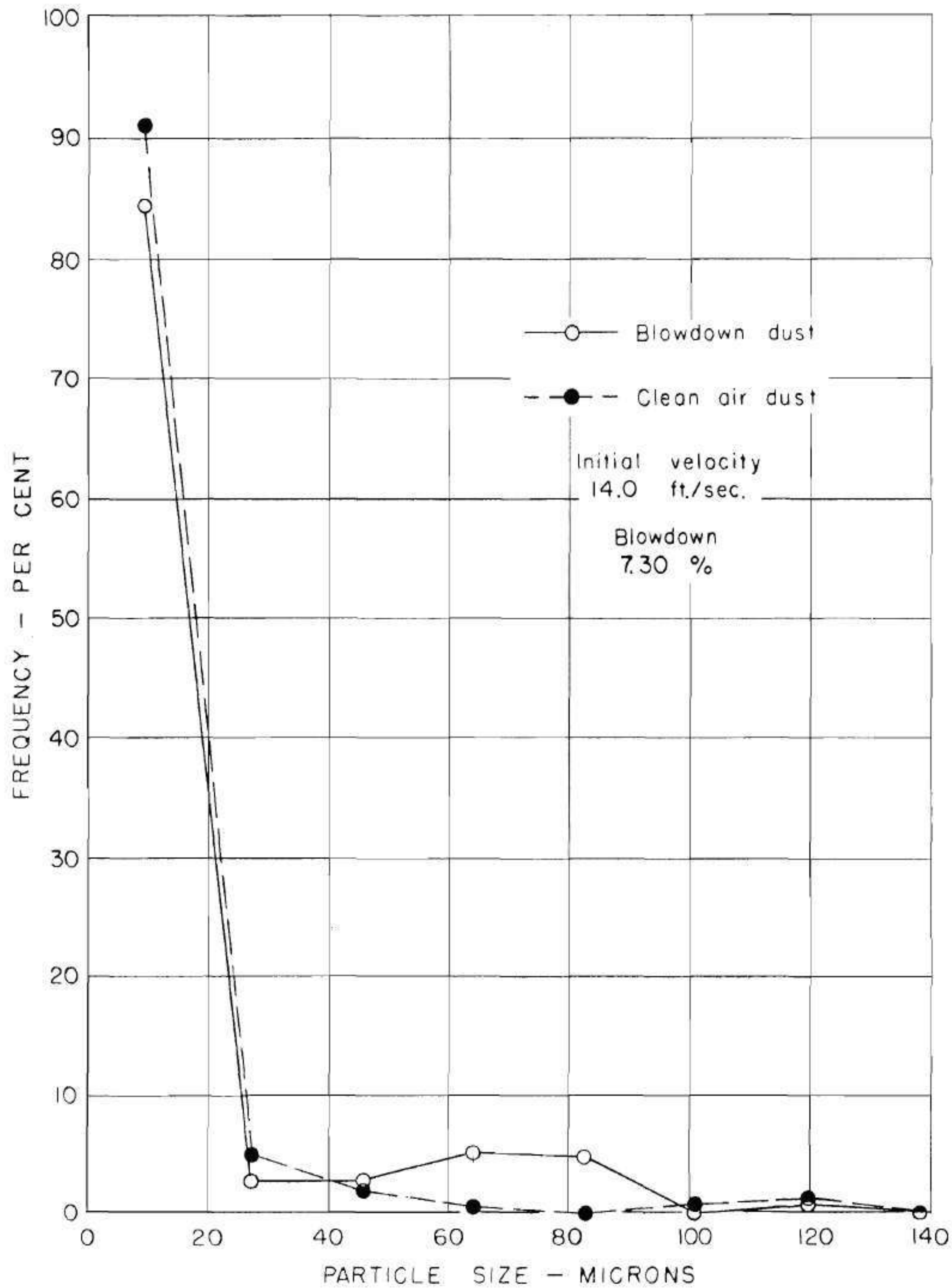

FIGURE 18
PARTICLE SIZE DISTRIBUTION
BLOWDOWN AND CLEAN AIR

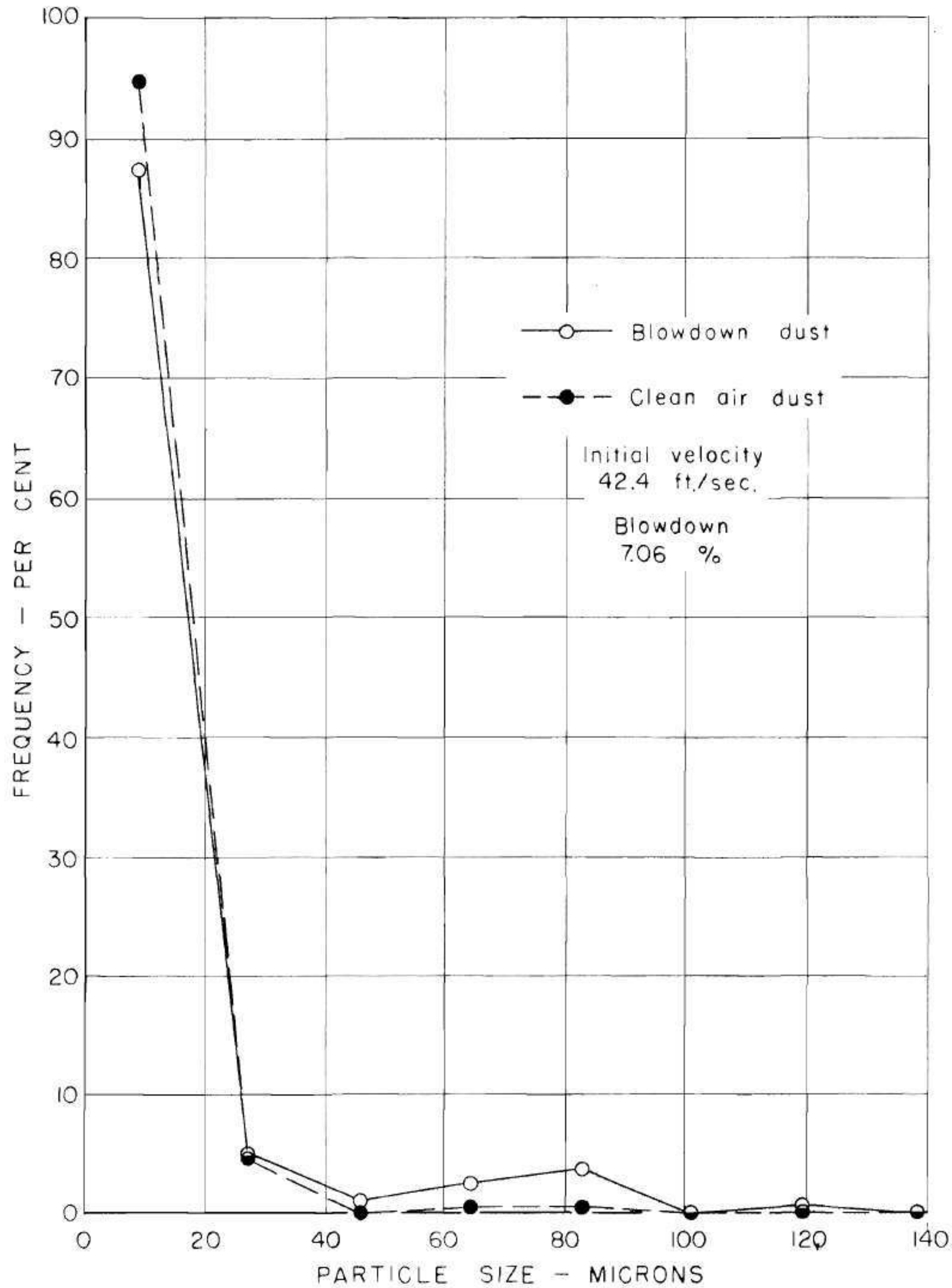

FIGURE 19
PARTICLE SIZE DISTRIBUTION
BLOWDOWN AND CLEAN AIR

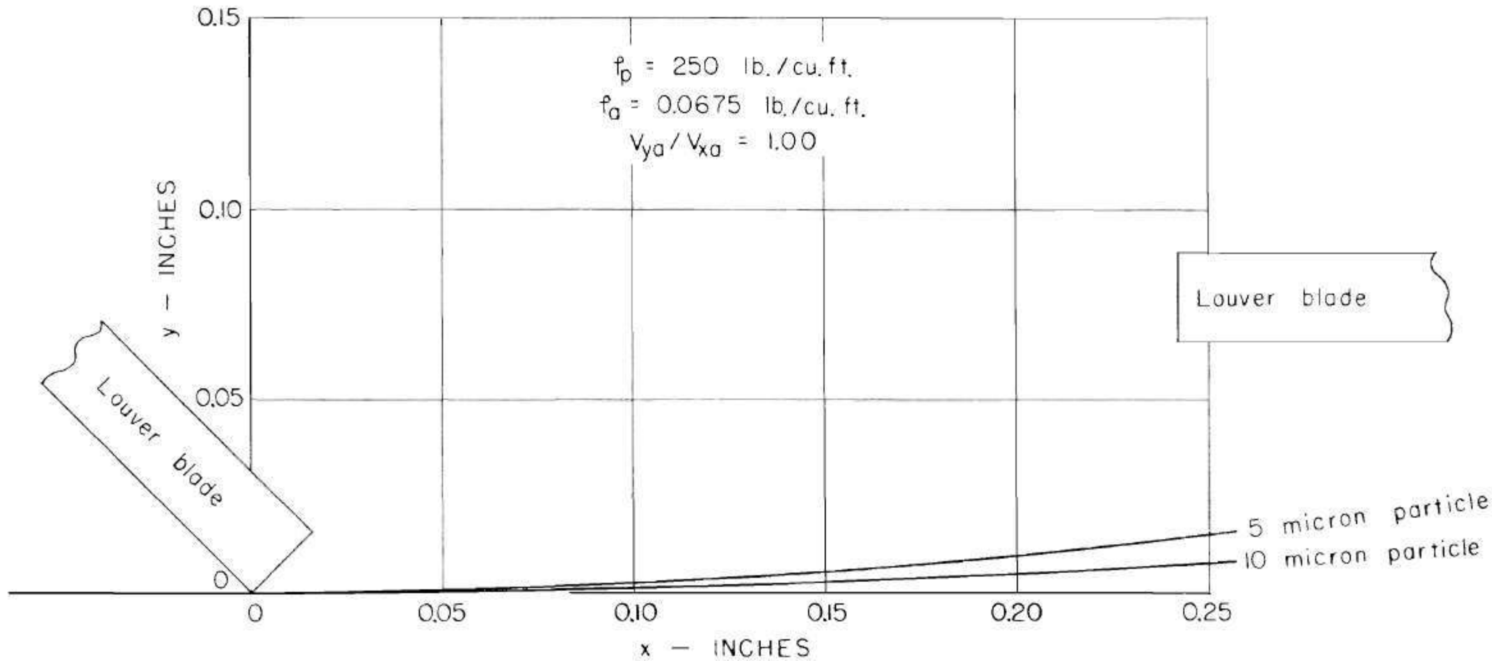

FIGURE 20
THEORETICAL PARTICLE PATHS NEAR
A LOUVER OPENING

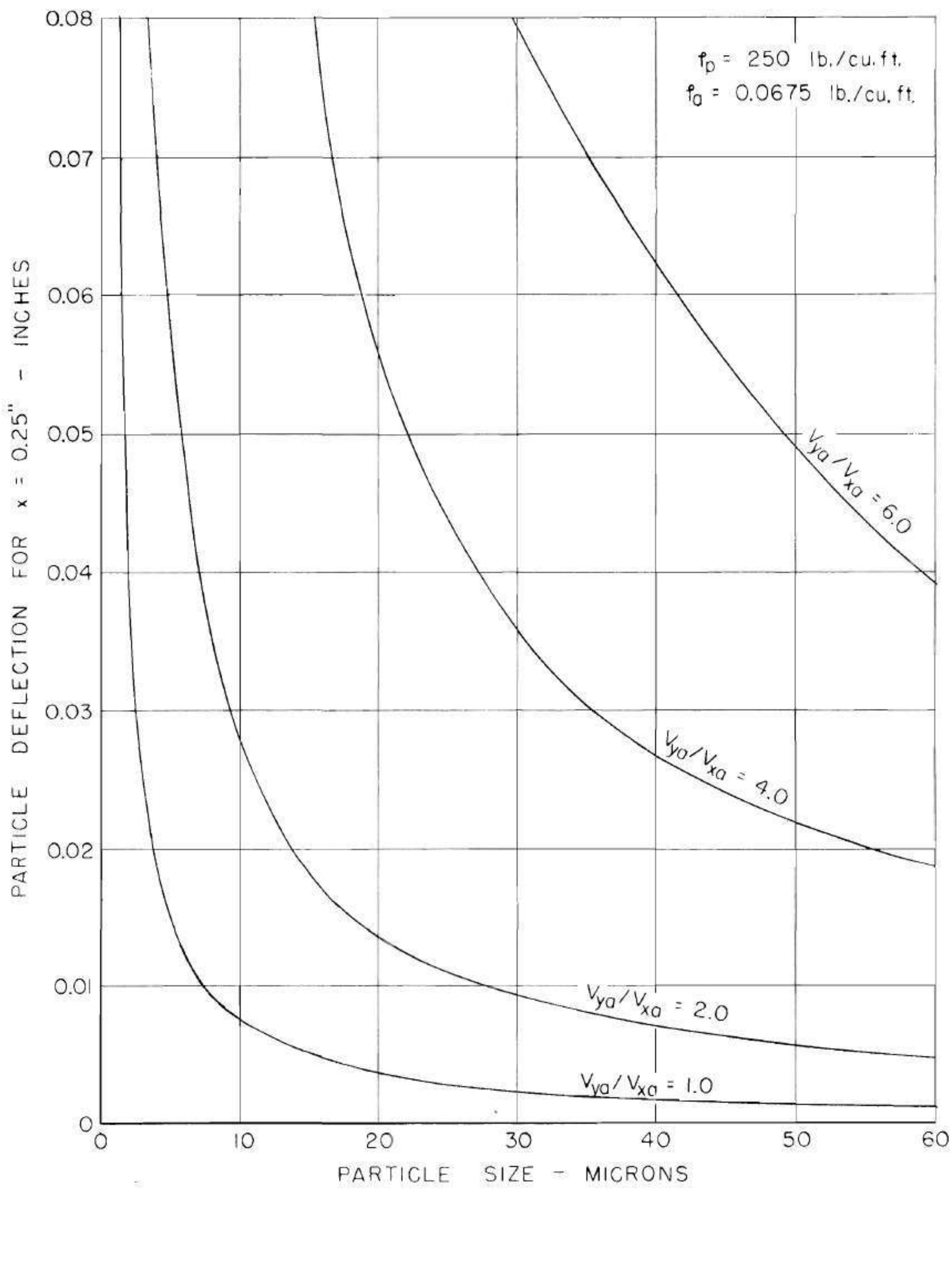

FIGURE 21
THEORETICAL PARTICLE DEFLECTIONS
FOR x = 0.25"

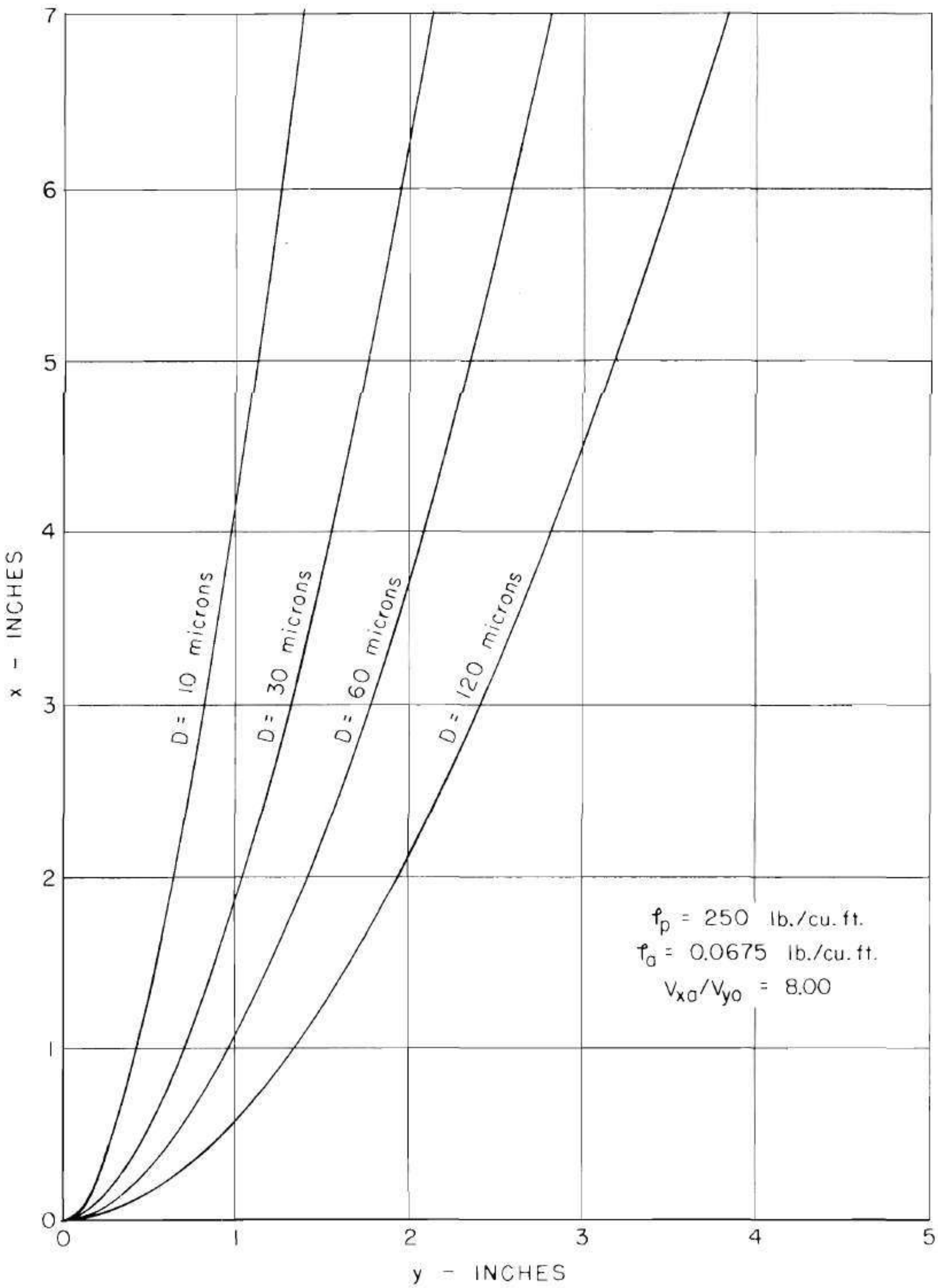

FIGURE 22
THEORETICAL PARTICLE PATHS
AFTER AN IMPACT

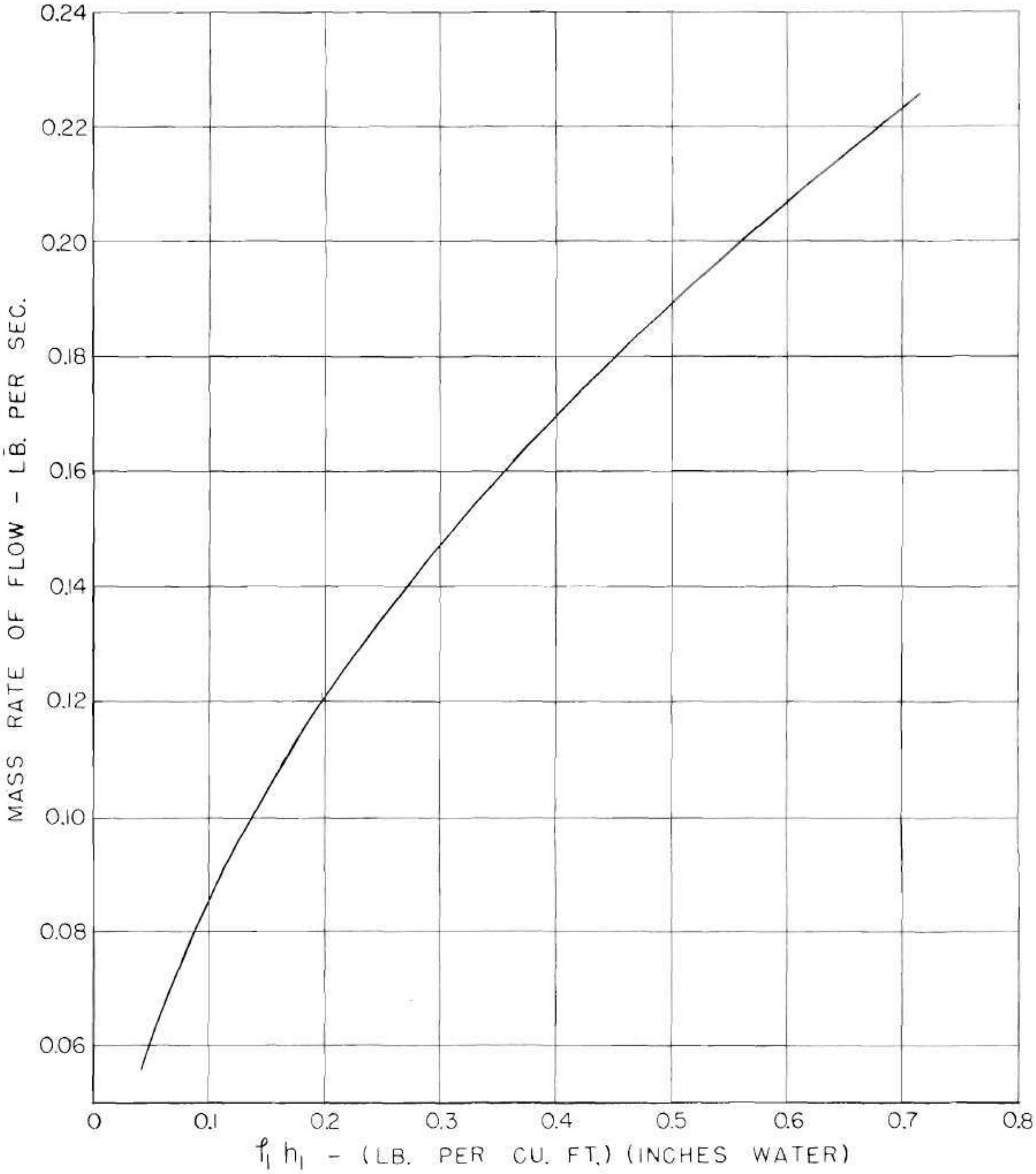

FIGURE 23

INLET ORIFICE CALIBRATION

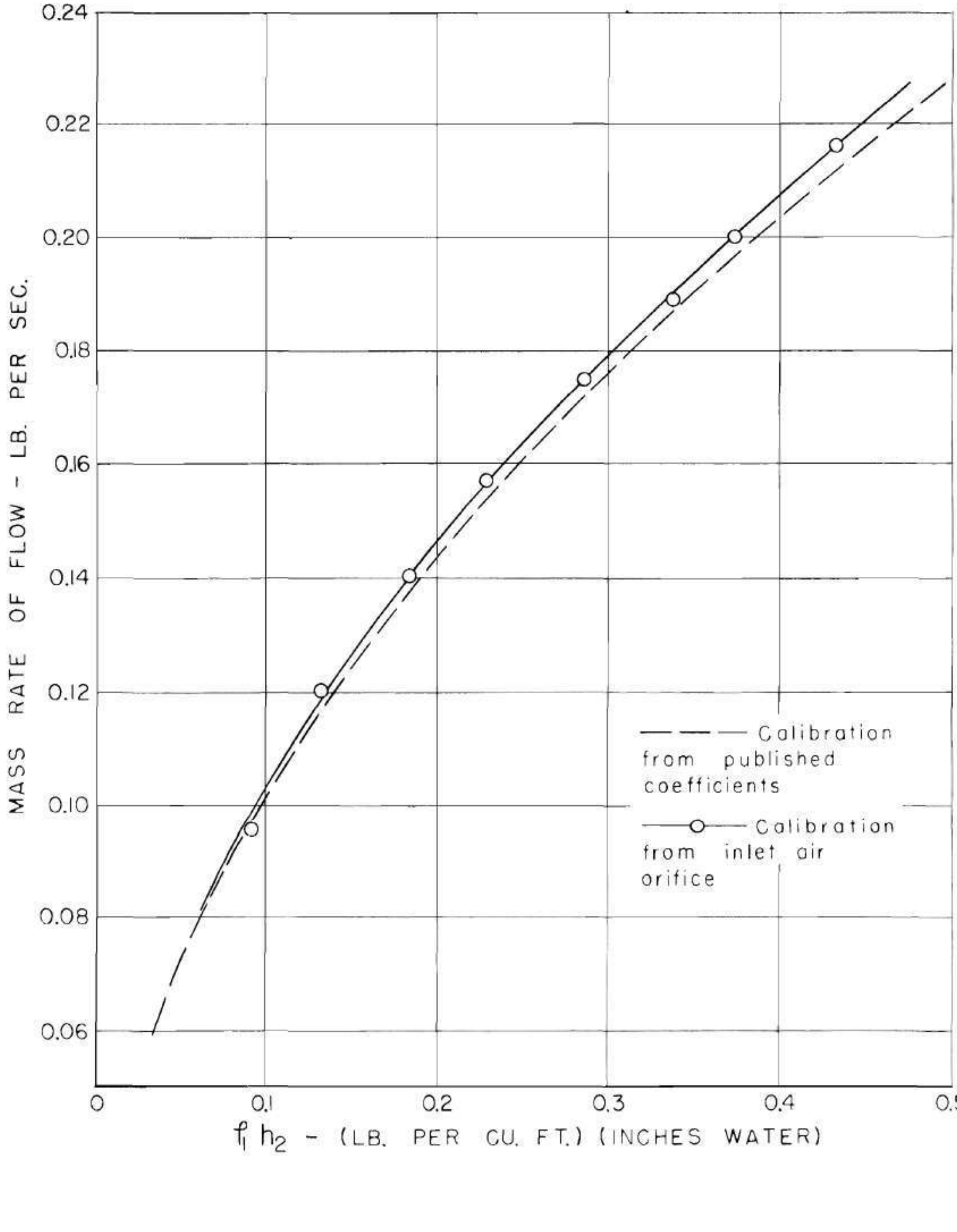

FIGURE 24
CLEAN AIR ORIFICE CALIBRATION

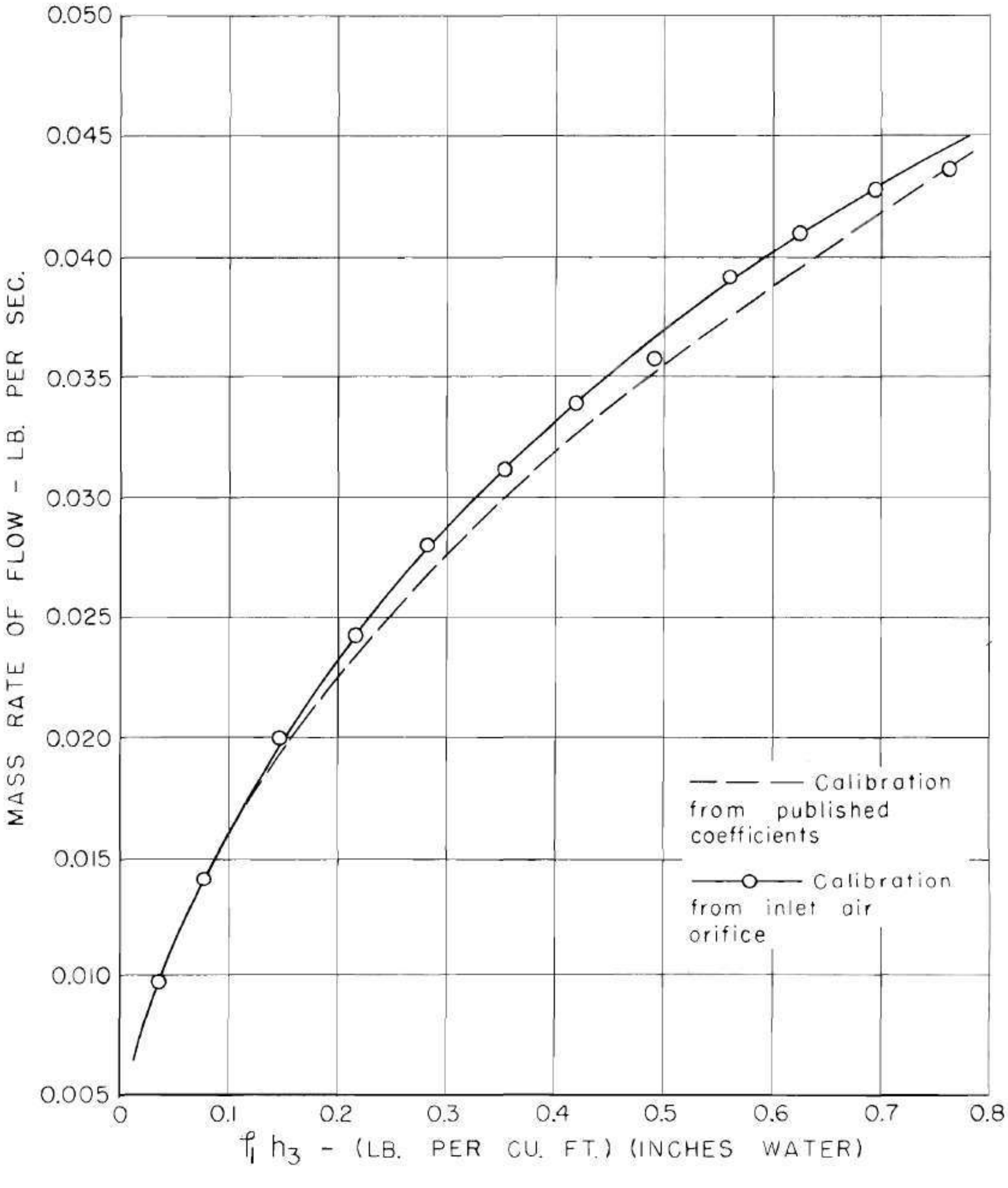

FIGURE 25
BLOWDOWN ORIFICE CALIBRATION

APPENDIX C

EXPERIMENTAL RESULTS

Table 1. Dust Separation Data

Run	Length of run (sec.)	Inlet dust (gm.)	Clean air dust (gm.)	Blowdown dust (gm.)	Dust loss (gm.)
1	238	68.0	8.5	59.2	0.3
2	200	68.0	4.8	63.1	-0.1
3	210	68.0	3.0	65.1	-0.1
4	255	68.0	2.2	65.9	-0.1
5	250	68.0	2.2	66.0	-0.2
6	255	68.0	2.0	66.1	-0.1
7	245	68.0	1.6	66.3	0.1
8	247	68.0	1.6	66.5	-0.1
9	251	68.0	0.9	67.2	-0.1
10	243	68.0	0.8	67.4	-0.2
11	1495	68.0	2.3	65.5	0.2
12	507	68.0	2.2	65.7	0.1
13	82	68.0	1.9	66.0	0.1
14	33	68.0	1.8	66.6	-0.4
15	16	68.0	1.6	66.7	-0.3
16	244	68.0	1.4	66.3	0.3
17	298	68.0	1.2	66.6	0.2
18	352	68.0	1.1	66.5	0.1
19	452	68.0	0.9	66.7	0.4
20	768	68.0	0.9	66.8	0.3

Table 2. Air Flow Data

Run	h_2* (in. H_2O)	h_{s2} (in. H_2O)	h_3 (in. H_2O)	h_{s3} (in. H_2O)	h_d (in. H_2O)	T_a (F)	T_d (F)	T_w (F)	Barometer (in. Hg.)
1	5.50	2.7	0	-	-	100	80	71	29.98
2	5.33	2.7	1.8**	-	-	100	86	73	29.04
3	5.13	2.5	5.5**	-	-	99	85	72	29.04
4	4.92	2.5	0.57	15.6	-	100	80	71	28.98
5	4.74	2.5	1.15	14.9	-	100	80	71	28.98
6	4.56	2.5	1.81	14.3	-	100	80	71	28.98
7	4.36	2.2	2.69	13.2	-	100	80	71	28.98
8	4.20	2.1	4.15	12.1	-	100	80	71	28.98
9	3.77	2.0	6.29	8.3	-	101	80	71	28.98
10	3.38	0.8	8.64	6.7	-	100	80	71	28.98
11	4.74	2.3	1.15	14.9	-	100	87	72	29.04
12	4.78	2.4	1.15	15.3	-	101	87	73	29.04
13	4.76	2.4	1.15	16.0	-	101	87	73	29.04
14	4.77	2.5	1.15	16.2	-	101	87	73	29.04
15	4.75	2.4	1.15	16.3	-	100	87	73	29.04
16	4.76	2.4	1.16	15.7	3.59	97	82	76	28.96
17	3.47	1.8	1.00	15.2	1.79	100	85	78	28.96
18	2.31	1.3	0.53	17.1	1.15	101	86	78	28.96
19	1.40	1.0	6.9**	-	0.70	106	90	80	28.96
20	0.47	1.3	4.15**	-	0.31	102	89	80	28.96

*See Appendix A for the meaning of the symbols.
**Flowrator in use. The reading is in cu. ft./mim. at 100 F and 14.7 Psia.

Table 3. Air Flow Results

Run	w_1 (lb./sec.)	w_2 (lb./sec.)	w_3 (lb./sec.)	Blowdown (per cent)	Initial air velocity (ft./sec.)	Blowdown air velocity (ft./sec.)
1	0.2010	0.2010	0	0	42.4	0
2	0.2003	0.1982	0.0021	1.03	42.2	7.2
3	0.1954	0.1948	0.0062	3.18	41.1	21.8
4	0.2003	0.1901	0.0102	5.08	42.2	35.8
5	0.2011	0.1869	0.0142	7.07	42.4	49.8
6	0.2013	0.1830	0.0183	9.10	42.5	64.4
7	0.2010	0.1792	0.0228	11.36	42.4	80.2
8	0.2043	0.1761	0.0283	13.8	43.1	99.5
9	0.2015	0.1671	0.0344	17.1	42.7	121.7
10	0.1985	0.1586	0.0399	20.1	42.1	141.1
11	0.2013	0.1871	0.0142	7.06	42.4	49.8
12	0.2017	0.1875	0.0142	7.05	42.4	49.8
13	0.2015	0.1873	0.0142	7.06	42.4	49.7
14	0.2017	0.1875	0.0142	7.05	42.4	49.7
15	0.2014	0.1872	0.0142	7.06	42.4	49.7
16	0.2014	0.1872	0.0142	7.06	42.2	49.6
17	0.1735	0.1603	0.0132	7.61	36.7	46.5
18	0.1410	0.1311	0.0099	7.04	29.8	34.7
19	0.1085	0.1008	0.0077	7.10	23.5	28.1
20	0.064	0.0590	0.0047	7.30	14.0	17.0

Table 4. Dust Concentrations

Run	G_1 (lb./sec.) (X 10+4)	G_2 (lb./sec.) (X 10+6)	Dust separated $(G_1-G_2)/G_1$ (per cent)	c_1 (lb./lb.) (X 10+3)	c_2 (lb./lb.) (X 10+5)
1	6.30	78.7	87.5	3.13	39.1
2	7.50	52.8	92.9	3.73	26.6
3	7.15	31.5	95.6	3.65	16.2
4	5.89	19.0	96.8	2.96	9.94
5	6.00	19.4	96.8	2.98	10.38
6	5.89	17.3	97.1	2.92	9.44
7	6.12	14.4	97.55	3.04	8.03
8	6.07	14.3	97.55	2.96	8.11
9	5.98	7.92	98.7	2.97	4.73
10	6.17	7.27	98.8	3.11	3.89
11	1.00	3.40	96.6	0.496	1.81
12	2.96	9.58	96.8	1.47	5.11
13	18.3	51.2	97.2	9.08	27.3
14	45.5	120.	97.4	22.6	64.0
15	93.9	220.	97.65	46.5	117.3
16	6.15	12.7	97.95	3.05	6.78
17	5.04	8.88	98.25	2.90	5.53
18	4.26	6.89	98.4	3.02	5.25
19	3.32	4.39	98.7	3.06	4.36
20	1.95	2.58	98.7	3.04	4.38

APPENDIX D

SOLUTION OF THE PARTICLE PATH EQUATIONS

SOLUTION OF THE PARTICLE PATH EQUATIONS

The x equation is

$$m \frac{dV_x}{dt} + C_d A \rho_a \frac{V_{xr}^2}{2} = 0$$

with the initial conditions

$$t = 0, \quad \begin{bmatrix} V_x = V_{xa} \\ x = 0 \end{bmatrix}$$

Separating the variables and making the substitution $V_{xr} = V_x$ gives

$$\frac{dV_x}{V_x^2} = -\frac{C_d A \rho_a}{2m} dt$$

Let

$$K = \frac{C_d A \rho_a}{2m}$$

where K is a constant for any given path. Then integration gives

$$\frac{1}{V_x} = Kt + C_1$$

Using the initial condition $t = 0$, $V_x = V_{xa}$ to evaluate the constant of integration gives

$$V_x = \frac{1}{Kt + \frac{1}{V_{xa}}}$$

Making the substitution

$$V_x = \frac{dx}{dt}$$

gives

$$dx = \frac{dt}{Kt + \frac{1}{V_{xa}}}$$

Integration gives

$$x = \frac{1}{K} \ln \left(Kt + \frac{1}{V_{xa}} \right) + C_2$$

Using the initial condition t = 0, x = 0 to evaluate the constant of integration C_2 gives

$$x = \frac{1}{K} \ln \left(KV_{xa}t + 1 \right)$$

Solving this expression for t gives

$$t = \frac{1}{KV_{xa}} \left(e^{Kx} - 1 \right)$$

The y equation is

$$m \frac{dV_y}{dt} - C_d A \rho_a \frac{V_{yr}^2}{2} = 0$$

with the initial conditions

$$t = 0, \quad \begin{cases} V_y = 0 \\ y = 0 \end{cases}$$

Separating the variables and making the substitution $V_{yr} = V_{ya} - V_y$ gives

$$\frac{dV_y}{(V_{ya} - V_y)^2} = \frac{C_d A \rho_a}{2m} dt$$

As before let

$$K = \frac{C_d A \rho_a}{2m}$$

where K is a constant for any given path. Then integration gives

$$\frac{1}{V_{ya} - V_y} = Kt + C_3$$

Using the initial condition $t = 0$, $V_y = 0$ to evaluate the constant of integration C_3 gives

$$V_y = V_{ya} + \frac{1}{Kt - \frac{1}{V_{ya}}}$$

Making the substitution

$$V_y = \frac{dy}{dt}$$

gives

$$dy = V_{ya}\, dt - \frac{dt}{Kt - \frac{1}{V_{ya}}}$$

Integration gives

$$y = V_{ya} t - \frac{1}{K} \ln\left(Kt + \frac{1}{V_{ya}}\right) + C_4$$

Using the initial condition t = 0, y = 0 to evaluate the constant of integration C_4 gives

$$y = V_{ya}t - \frac{1}{K}\ln\left(KV_{ya}t + 1\right)$$

Eliminating t with the x solution gives the expression for the particle path

$$y = \frac{1}{K}\left\{\frac{V_{ya}}{V_{xa}}\left(e^{Kx} - 1\right) - \ln\left[\frac{V_{ya}}{V_{xa}}\left(e^{Kx} - 1\right) + 1\right]\right\}$$

where

$$K = \frac{C_d A \rho_a}{2m}$$

But since the particles have been assumed to be spheres

$$A = \frac{\pi D^2}{4}, \qquad m = \frac{\pi D^3 \rho_p}{6}, \qquad C_d = 0.44.$$

K then for the spherical particles becomes

$$K = \frac{0.33\,\rho_a}{D\,\rho_p}$$

APPENDIX E

CALIBRATION OF ORIFICE METERS

CALIBRATION OF ORIFICE METERS

The orifice meters which were used in this investigation were constructed in accordance with the specifications for thin plate orifices given in the A.S.M.E. Research Committee Report on Fluid Meters. (9) Standard flange pressure taps were used on each orifice meter. The taps were located one inch upstream and one inch downstream from the respective faces of the orifice plate.

The flow equation for the thin plate orifice is

$$w = 0.0997 \frac{C}{\sqrt{1 - \beta^4}} D_2^2 \sqrt{\rho_1 h}$$

where
- w = flow rate--lb./sec.
- C = coefficient of discharge
- D_2 = orifice diameter--inches
- β = D_2/D_1
- D_1 = pipe diameter--inches
- ρ_1 = upstream air density--lb./cu.ft.
- h = orifice pressure differential--inches water.

The Fluid Meters Report gives experimentally determined values of the expression

$$\frac{C}{\sqrt{1 - \beta^4}}$$

The values are tabulated for different pipe diameters, Reynold's numbers, β ratios, and pressure tap arrangements.

The specifications for the three orifices were:

	inlet air orifice	clean air orifice	blowdown orifice
Pipe diameter	3"	3"	1.5"
β ratio	0.650	0.700	0.550
Orifice diameter	1.995	2.148	0.886

To solve the flow equation for the flow rate corresponding to a given $\rho_1 h$ product requires a trial and error proceedure. In order to eliminate the necessity of the trial solution, the air temperature was assumed to be 100 degrees Fahrenheit and a curve of w versus the $\rho_1 h$ product was plotted for each orifice. For each run the air temperature was within six degrees of 100 degrees Fahrenheit. This difference does not affect the third significant figure in w. These curves are shown in Figures 23, 24 and 25.

The clean air orifice and the blowdown orifice were calibrated using the inlet air orifice as a standard. The inlet air orifice was used as the standard because it was proceeded by a longer run of straight pipe than were the other orifices. Thus the published coefficients were applicable to the inlet air orifice with the greatest accuracy. The sixty inch run of straight pipe upstream from the inlet air orifice is as is recommended by Rhodes. (10) To calibrate the clean air orifice, the blowdown was closed so that the flow through the clean air orifice and the initial air orifice would be the same. With the clean air orifice calibrated, the blowdown orifice was calibrated by taking the difference between the flow through the inlet air orifice and the flow through the clean air orifice. The calibrations are shown in Figures 24 and 25. For all flow rates the calculated flow did not differ from the calibrated flow by more than four per cent of the calibrated flow. The calibrated flowrator was used to check the low flow calibration of the blowdown orifice. The check showed a difference of 8.3 per cent.

The flow rates for the test runs were determined by using the experimental calibration curves for the clean air and the blowdown orifice. The inlet air orifices was not used to measure the total air flow becuase it did not include the air which was introduced by the dust feeder.

Table 5. Calibration of Orifice Meters

Barometer = 28.98 in. hg. Dry bulb temp. = 88 F

Gas constant = 53.9 ft.-lb./lb. F abs. Wet bulb temp. = 78 F

Run	T_a (F)	h_1 (in.H_2O)	h_{s1} (in.H_2O)	h_2 (in.H_2O)	h_{s2} (in.H_2O)	h_3 (in.H_2O)	h_{s3} (in.H_2O)
1	97	9.24	19.4	6.32	3.3	0	-
2	98	7.90	16.9	5.41	2.9	0	-
3	99	7.05	15.4	4.87	2.6	0	-
4	100	6.07	13.5	4.11	2.1	0	-
5	100	4.91	11.2	3.31	1.8	0	-
6	101	3.90	9.3	2.66	1.4	0	-
7	101	2.91	7.4	1.90	1.2	0	-
8	101	1.81	5.2	1.24	0.8	0	-
9	103	9.14	19.2	3.98	2.0	11.03	8.5
10	104	9.11	19.4	4.04	2.1	10.03	8.9
11	104	9.07	19.4	4.09	2.1	9.05	9.3
12	105	9.02	19.5	4.16	2.1	8.07	9.9
13	105	8.93	19.7	4.28	2.2	7.10	10.2
14	105	8.85	19.8	4.32	2.2	6.09	11.0
15	102	9.93	14.7	5.01	2.6	5.10	8.5
16	103	9.77	17.9	5.12	2.6	4.10	9.0
17	103	9.69	18.0	5.28	2.8	3.10	9.6
18	103	9.60	18.3	5.46	2.8	2.11	10.3
19	103	9.48	19.0	5.64	2.0	1.13	11.1
20	103	9.39	18.8	5.83	2.0	0.53	11.8

Table 5. Calibration of Orifice Meters (Continued)

Run	w_1 (lb./sec.)	w_2 (lb./sec.)	w_3 (lb./sec.)	$\rho_1 h_1$ (in. H_2O X lb./cu.ft.)	$\rho_1 h_2$ (in. H_2O X lb./cu.ft.)	$\rho_1 h_3$ (in. H_2O X lb./cu.ft.)
1	0.217	0.217	0	0.660	0.434	0
2	0.200	0.200	0	0.560	0.371	0
3	0.189	0.189	0	0.498	0.333	0
4	0.175	0.175	0	0.425	0.280	0
5	0.157	0.157	0	0.342	0.225	0
6	0.140	0.140	0	0.270	0.181	0
7	0.121	0.121	0	0.200	0.129	0
8	0.096	0.096	0	0.124	0.083	0
9	0.2149	0.1713	0.0436	0.646	0.269	0.762
10	0.2148	0.1720	0.0428	0.645	0.273	0.693
11	0.2141	0.1731	0.0410	0.642	0.277	0.624
12	0.2138	0.1746	0.0392	0.639	0.281	0.557
13	0.2128	0.1772	0.0356	0.633	0.289	0.490
14	0.2115	0.1776	0.0339	0.627	0.292	0.420
15	0.2230	0.1919	0.0311	0.696	0.341	0.352
16	0.2220	0.1940	0.0280	0.690	0.348	0.283
17	0.2211	0.1969	0.0242	0.684	0.359	0.214
18	0.2199	0.2000	0.0199	0.677	0.372	0.146
19	0.2174	0.2033	0.0141	0.662	0.383	0.078
20	0.2164	0.2066	0.0098	0.655	0.387	0.037

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